Declaration

The work submitted in this thesis is the result of investigations carried out by the author. The material in this thesis has not been accepted in any substance for any degree, and is not concurrently being submitted in candidature for any other degree.

Signed : _____

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Marion Edwards

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Abstract of the thesis entitled "Visual functions before and after LASIK"
submitted by Jay Wing-wo Chan
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at The Hong Kong Polytechnic University in 2002

Abstract

Laser in situ keratomileusis (LASIK) is a relatively new technique to reduce refractive error, and many clinical studies have shown that the visual outcomes after LASIK are better than with previously-used procedures such as radial keratotomy (RK) and photorefractive keratectomy (PRK). Studies of LASIK outcomes have shown that corneal recovery time after LASIK is relatively short, nevertheless visual problems such as glare and halos, are reported by a small percentage of patients.

The objective of this longitudinal study was to characterize the visual changes occurring within one year of LASIK treatment. Three aspects of visual function, contrast sensitivity, glare sensitivity and corneal clarity were investigated before and after LASIK treatment, so that by comparing the results the effects of LASIK on the visual functions were found and recovery time determined.

In the contrast sensitivity study, a computer-base contrast sensitivity test was used. Subjects were asked to respond "yes" if the target was seen and "no" if it was not. Contrast sensitivity threshold values were determined using a staircase protocol. Contrast sensitivity was measured for seven spatial frequencies, prior to LASIK and one week, one month, three months, six months and one year post-LASIK. There was a general depression of contrast sensitivity after LASIK treatment and contrast sensitivity took at least six months to recover to the pre-operative level. This non-permanent depression is probably related to optical factors.

In the glare sensitivity study, a glare tester was developed. Contrast sensitivity was measured with and without glare prior to LASIK and at the time intervals shown above. There was no statistically significant extra glare detected after LASIK treatment. This negative result may be because pupil miosis under glare condition reduced the diffracted and scattered light from the peripheral area of the LASIK treatment zone. Subjective glare sensation was experienced immediately post-operatively, however this had decreased just one day post-surgery.

In the corneal clarity study, a new method to measure corneal clarity objectively

and quantitatively was developed, and proved to be able to detect small amount of corneal clarity change. The color intensitity of a photograph of a carefully controlled slit lamp optic section of the cornea was measured and analyzed to provide a measure of corneal clarity. Corneal clarity decreased and returned to pre-treatment levels one month post-treatment. The haze noted was very subtle and would be unlikely to affect best-corrected visual acuity.

LASIK is an effective surgical alternative for the reduction of moderate myopia. LASIK causes a temporary decrease in contrast sensitivity and corneal clarity, and a sensation of glare which usually subsides within a day of surgery.

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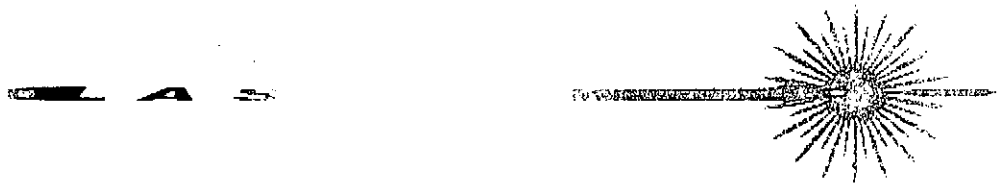
Chapter 1

Review



1.1 Introduction

About 70% of the Hong Kong population under 50 years of age is myopic (Goh and Lam, 1994). Refractive surgery offers permanent correction of myopia and other refractive errors, and patient satisfaction is improving as a result of improved outcomes due to advances in technology and in the technique itself. Laser in situ keratomileusis (LASIK) is a relatively new technique to reduce refractive error, and clinical studies have shown that the visual outcomes after LASIK are better than those after radial keratotomy (RK) and photorefractive keratectomy (PRK). Animal studies of LASIK outcomes have shown that corneal recovery time after LASIK is relatively short; nevertheless visual problems such as glare and halos, are reported by a small percentage of patients. These visual complaints are believed to relate to subtle changes that ordinary clinical tests may

not be sensitive enough to detect. Specially designed tests are needed in order to see the real visual outcomes after LASIK treatment.

This thesis describes a one-year longitudinal study carried out with the collaboration of the Hong Kong Laser Eye Center (HKLEC). The study focused on subtle visual changes occurring within one year of LASIK treatment. Three aspects of visual function, contrast sensitivity, glare sensitivity and corneal clarity were investigated before and after LASIK treatment so that by comparing the results, the effect of LASIK on the visual functions were found and recovery time determined.

Potential LASIK patients have the right to know the likely outcomes and the risks associated with the treatment. Local ophthalmologists wish to improve the treatment protocol and to provide the best care possible to patients in this "myopic city".

By way of an introduction, in this chapter the structure, physiology, and healing response of the cornea will be described and recent trends in refractive surgery

reviewed.

1.2 Anatomy and physiology of the cornea

The cornea is the anterior refractive surface of the eye. Its refractive index (1.376) and its radius of curvature (7.0 to 8.5mm) give the entire cornea an average refractive power of 43.0D, 70% of the total refractive power of the eye. The cornea comprises five different layers. The first is the epithelium, itself consisting of five layers of cells. Squamous cells, the most superficial, are flat in shape and the outermost cells have microvilli projecting into the tear film trapping tear fluid and preventing drying of the epithelial cells. The middle layer comprises wing cells, which are more column-like in shape. The innermost layer is made up of closely packed columnar basal epithelial cells.

The second layer of the cornea is Bowman's membrane, which is a transparent tissue, made up of uniform collagenous fibrils. The third layer is the stroma, which makes up of 90% of the cornea. Sayers et al. (1982) stated that the stroma comprises over 200 sheets of lamellar fibrils, each with a thickness of 1 to 2 μm and diameter of approximate 36 nm. The lamellae inside this layer are loosely

adhered to each other. The fourth layer is Descemet's membrane. The fifth layer of the cornea is the endothelium, which is a single cell layer with limited cell reproductive capacity and which plays an important role in maintaining the hydration of the cornea. Any loss of cells, for example through aging, trauma or surgery, will be compensated for by increased cell size and decreased cell density. As the cornea is an avascular structure, it has its own metabolic system to maintain its integrity. The endothelial pump consumes energy in the form of ATP, which is generated by the break down of glucose, derived from aqueous humor, in glycoloysis and the Krebs cycle, in order to maintain the corneal hydration. Damage to either the epithelium or endothelium will lead to corneal swelling and cloudiness. Endothelium damage is far more serious and may cause marked and sometimes permanent swelling and loss of transparency.

1.3 Corneal transparency

Many theories have been offered to explain corneal transparency. Caspersson and Engström (1946) suggested that it is the result of the alignment of rows of the fibrils within the stroma. Light rays pass down rows of fibrils, being reflected in transit, to finally emerge undeviated. The gradation in refractive index between

the collagen fibrils and ground substance limits reflection at the fibril surface. Another theory, widely accepted in the past, is that the transparency of the cornea is the result of all the corneal components having identical refractive indices. Aurell and Holmgren (1953) attempted to measure the refractive indices in the separate components and showed that this hypothesis was valid. They found that the refractive index of dry collagen is 1.547, whereas that of pressure-extracted corneal fluid is 1.342, showing that the refractive indices of the corneal components are different. The results of the above-mentioned experiment are unlikely to reflect the cornea in vivo (Smith, 1970), and indeed it has been found that the refractive index varies throughout the cornea (Maurice, 1957; Bettelheim and Kumbar, 1977; Bettelheim and Magrill, 1977; McCally and Farrell, 1982). Maurice (1957) pointed out that if individual collagen fibrils scattered light independently, the stroma would be opaque. As the cornea is transparent, a phase relationship must exist between electromagnetic fields emanating from individual fibers, resulting in destructive interference of the scattered wavelets and limiting the intensity of the scattering. He believed that the arrangement of the fibrils is lattice, i.e. there is a high degree of uniformity in the size of the corneal fibrils, and a high degree of regularity in the arrangement. The rapid loss of corneal

transparency which occurs when local pressure is applied, and which disappears on removal of the distorting force, could be explained by local disordering of the lattice. The loss of transparency disappeared immediately on removal of the distorting force. However, Potts (1962) used election micrographs found that the regularity of spacing is not present in other transparent ocular structures. Goldman and Benedek (1967) studied dogfish and concluded that a lattice arrangement of collagen fibrils was not a necessary condition for corneal transparency. They also observed that the scleral collagen fibrils are of very variable diameter and that the intervening spaces are large relative to the wavelength of light. They suggested that these features are more important than the lack of lattice arrangement in accounting for scleral opacity.

Smith (1970) stated that the factors making the cornea highly transparent are the very small size of the collagen fibrils and the close similarity between the refractive indices of the fibrils and the ground substance. Goldmann et al. (1968) used diffraction theory to explain corneal transparency. According to this theory, periodic fluctuations in refractive index over distances which are small compared with the half wavelength of light do not produce scattering. Therefore, the path of

light rays will not be affected by a structure substantially smaller than their wavelength. Farrell et al. (1973) found that measurements of light scattering supporting the theory of short-range ordering of collagen fibrils rather than a strict lattice arrangement.

Current understanding of corneal transparency favors a short-range ordering of fibril structure such that fluctuations in refractive index fall within the minimum dimensions of the wavelength of light, thus enabling a high degree of transparency.

1.4 Corneal wound healing

If any kind of corneal trauma occurs, a series of wound healing responses takes place and has adverse effects on corneal transparency. Corneal trauma can be classified according to the depth of the wound, for example, epithelial defects, epithelial and superficial stromal defects, deep stromal defects and full-thickness defects. Each lesion involves specialized wound healing events (Parrish and Chandler, 1998).

1.4.1 Epithelial defects

The healing of a simple corneal epithelial abrasion involves a number of complex active processes. Epithelial defects heal by the sliding and proliferation over the wound of adjacent epithelial cells. The wing cells adjacent to the defect flatten and slide first, so that a thin layer of cells covers the abraded area, this process takes place within 24 to 96 hours. The time to close the abrasion will double if there is no basal lamina (Khodadoust et al., 1968; Maurice, 1968). The epithelial cells surrounding the abrasion begin to replicate within 24 hours after trauma and eventually restore the epithelial layer to its normal thickness. There is evidence that without an intact corneal limbus, the corneal epithelial healing may be impaired because limbal cells are the stem cells that divide to restore wounded corneal epithelium (Huang et al., 1988; Tseng, 1989; Chen and Tseng, 1990; Huang and Tseng, 1991).

The abrasion will be coated by a glycoprotein, fibronectin, before it is covered by epithelium. Fibronectin is present in serum and is produced by many kinds of cells, for example, liver cells, vascular endothelium, macrophages and fibroblasts. The fibronectin present in corneal abrasion is most likely from serum. The production

of fibronectin begins two to four days after trauma, by which time most epithelial defects are covered with epithelial cells. It is believed that fibronectin will form a matrix that provides a platform for the migration of the epithelial cells adjacent to the abrasion (Clark et al., 1983; Nishida et al., 1983). After a corneal abrasion, actin filaments are present in the leading edges of the sliding cells (Gipson and Keezer, 1982) and the actin filaments track across the fibronectin matrix to cover the epithelial defect. The accumulation of fibronectin on the defect and the reorganization of actin filaments within the epithelial cells are key elements in the healing of abrasions.

1.4.2 Epithelial and superficial stromal defects

The process of epithelial wound healing in this kind of defect is the same as for an epithelial abrasion. However, the stroma is usually not an ideal structural platform for epithelial wound healing because of its roughness. Bowman's layer and the stroma are not regenerated and may be replaced by collagenous scar tissue or the defect may be filled in by thickened epithelium that forms a facet. (Parrish and Chandler, 1998).

1.4.3 Deep stromal defects

The repair of deep stromal defects occurs in a similar fashion, except that the deposition of collagenous scar tissue is a component of the wound healing process. It takes weeks for a corneal stromal wound to heal completely, but changes in the adjacent viable stromal keratocytes begin to take place almost immediately (Weimar and Haraguchi, 1965). Normal corneal stroma is composed of type I collagen, however large amounts of type III collagen are found in corneal scars tissue (Newsome et al., 1981).

1.4.4 Full-thickness defects

Yanoff and Fine (1982) described a six-phase wound healing response after full-thickness corneal injury. They are the time immediately after injury (first phase), leukocytic phase, epithelial phase, fibroblastic phase, endothelial phase and a late phase. In the first phase, the retraction of collagen in the wound area causes anterior and posterior wound gape. Fibrinogen in the aqueous cleaves to fibrin on contact with the cut portions of the stroma and forms a fibrin plug. Stromal edema starts.

The leukocytic phase begins approximately 30 minutes after the injury. Leukocytes migrate to the damaged area via the tears, aqueous humor, and limbal blood vessels. These cells are mildly phagocytic and release a variety of enzymes. Mononuclear cells accumulate at the limbus and may migrate to the wound 12 to 24 hours after the injury.

The epithelial phase begins one hour after injury and involves sliding and proliferation as described above. Epithelium migrates rapidly over sloping or gradually inclined defects. If there is an anterior wound gape, the epithelium usually fills in the area until stromal healing fills the defect with scar tissue and the epithelium retracts.

The fibroblastic phase begins 12 hours after injury and is related to the onset of successful epithelial wound healing. The stromal keratocytes adjacent to the corneal laceration are activated and become similar to fibroblasts. Typical scar glycosaminoglycans and type III collagen are produced. Monocytes may undergo metaplastic changes and participate in the fibroblastic phase if the laceration is near the limbus.

The endothelial phase begins 24 hours after injury and involves sliding of the endothelial cells. The endothelial cells that cover the area of injury secrete a new Descement's membrane over several weeks.

The late phase begins one week after injury. The cellularity of the wound decreases and the collagen fibrils that were originally secreted in haphazard directions becomes oriented more like normal type I corneal collagen.

1.5 Refractive errors

A refractive error is present, if distance light rays, after passing through the optical media including the cornea and the unaccommodated crystalline lens, do not focus on the retina. In the simplest terms, the light rays may fall behind the retina causing hyperopia or in front of the retina causing myopia. Those affected will suffer from different degrees of blurred vision, depending on the seriousness of the error and the amount of accommodation in play.

1.5.1 Myopia

Myopia is a condition in which, with accommodation relaxed, parallel (distance)

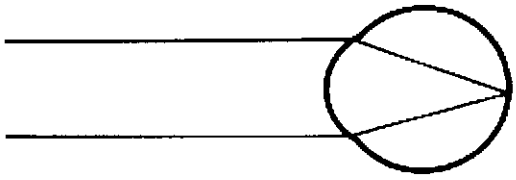
rays of light converge to a focus in front of the retina. In myopia the axial length of the eye can be normal and the focal length of the optical system shorter than normal, or the axial length of the eye can be longer than normal and the focal length of the eye's optical system normal. Myopia may be due to either situation, or a combination of both, although an abnormally long axial length is nearly always involved (axial myopia).

1.5.2 Hyperopia

Hyperopia is the condition in which, with accommodation relaxed, parallel rays of light converge to a focus behind the retina. As in myopia, hyperopia can occur in different forms. The axial length of the eye can be normal and the focal length of the optical system longer than normal, or the axial length can be shorter than normal and the focal length normal. Alternatively hyperopia may result as a combination of the above two situations. Fig. 1.1 illustrates the myopic and hyperopic conditions.

Fig. 1.1. (A) Emmetropic eye. (B) Myopic eye with short focal length. (C) Myopic eye with long axial length. (D) Hyperopic eye with long focal length. (E) Hyperopic eye with short axial length.

(A)



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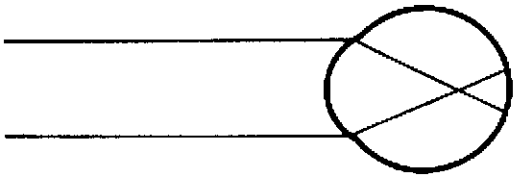

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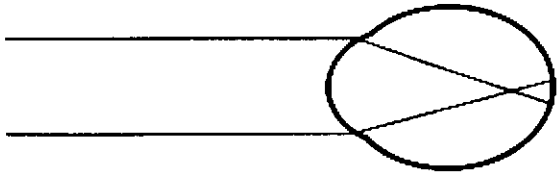

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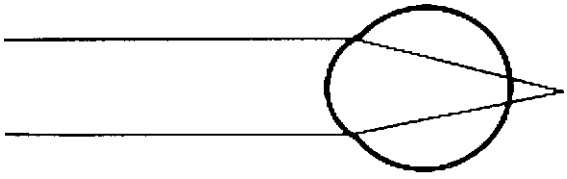

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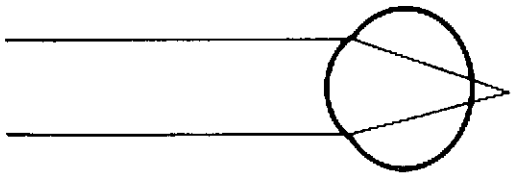
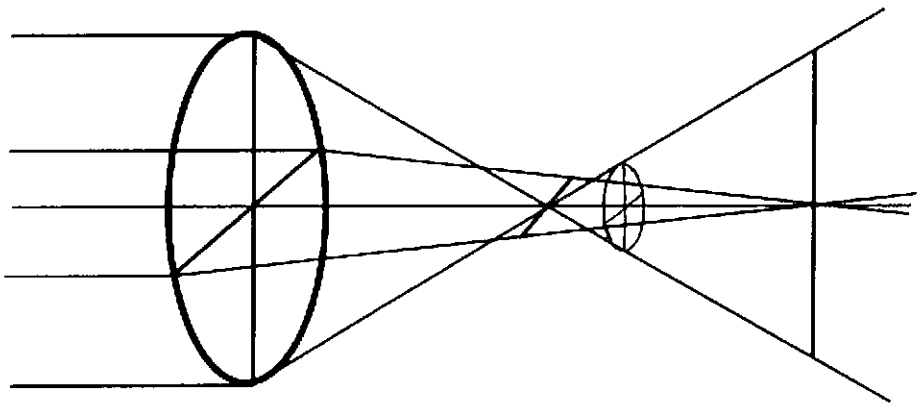


1.5.3 Astigmatism

Astigmatism is a refractive condition in which the eye's optical system is incapable of forming a point image of a point object. This is because the refracting power of the optical system varies from one meridian to another. In regular astigmatism, the meridian of greatest refraction and the meridian of least refraction are 90 degrees apart. The amount of astigmatism is equal to the difference in refracting power of the two principal meridians. Fig. 1.2 shows the refraction which takes place at a toric surface. Instead of a single point image being formed for each object point, the image consists of two focal lines, one parallel to each other of the principal meridians. The circle of least confusion is located between the two focal lines.

Fig. 1.2. Refraction at a toric surface



1.6 Ways to correct refractive errors

There are several ways to correct refractive error. The most common is the use of optical aids – spectacles or contact lenses – to make the light rays focus on the retina. In recent decades, scientists and surgeons have developed surgical techniques to reduce refractive errors. This kind of surgery is classified as refractive surgery.

1.7 Classification of refractive surgery

Waring (1985) classified refractive surgery into three classes: refractive keratoplasty, intraocular lenses, and posterior sclera support. Refractive keratoplasty can be further divided into many sub-classes. (1) In lamellar refractive keratoplasty, the corneal refractive power is altered by placing a lenticule on or within the cornea. (2) In keratotomy the corneal radius and refractive power is changed by making a partial thickness incision into the cornea. (3) Keratectomy involves excision of a piece of cornea to change the corneal refractive power either by mechanical means or by pulsed laser, and there are many different techniques in this last class, such as photorefractive keratectomy, laser in situ keratomileusis (LASIK) and intrastromal photodisruption. (4) In

penetrating keratoplasty the central portion of the cornea is replaced by donor tissue and (5) in thermal keratoplasty heat is applied to the cornea to change its curvature.

1.8 Refractive surgery in the past

1.8.1 Radial keratotomy (RK)

Radial keratotomy is a surgical technique in which incisions are made in the cornea in order to flatten it and produce a reduction in its refractive power. As long ago as the 19th century, a Dutch ophthalmologist, Herman Snellen, proposed the use of incisions to alter the curvature of the human cornea. Schiotz, in 1885, confirmed that significant degrees of corneal flattening occurred after the placement of corneal incisions tangential to the steep meridian of the cornea (Assil, 1999). Bates (1894) reported that flattening of the corneal surface along the scar meridian occurred in patients with radial corneal scars. Lans (1898) demonstrated in rabbits that anterior corneal incisions resulted in corneal flattening along the meridian of incisions. Sato (1953) reported a comprehensive study of a surgical approach to corneal flattening that consisted of making numerous radial incisions on both the epithelial and endothelial corneal surfaces.

However, the damage thus caused to the endothelium resulted in corneal edema and therefore, the posterior incision technique was abandoned.

1.8.2 Photorefractive keratectomy (PRK)

Taboada et al. used an excimer laser on the cornea. They found that the epithelium cells are very sensitive to a krypton fluoride laser (Taboada and Mikesell, 1981). Trokel et al. (1983) used an excimer laser to remodel a bovine cornea, and again demonstrated that the adjacent tissue does not suffer from thermal damage and that the stromal lamellae adjacent to the incision show no evidence of disorganization. They suggested that excimer laser could be used for refractive surgery.

Photorefractive keratectomy is a surgical procedure using excimer laser to remove part of the corneal tissue in order to alter its refractive power. Removal of the epithelium is needed before ablation takes place. The epithelium can be removed manually, chemically or by laser ablation.

1.8.3 Laser in situ keratomileusis (LASIK)

Four decades ago, Krwawicz (1961) was one of the few investigators working in refractive surgery. He suggested a new surgical technique aimed at correcting the refractive error of aphakic eyes by changing the central corneal curvature with the help of intralamellar implantation of a small plastic lens. The lens was removed when the change in corneal curvature had been fixed by the healing process.

In 1970, Barraquer conceived and developed the concepts of keratophakia and keratomileusis in which the corneal tissue was removed using a microkeratome. He was the first to use a mathematical basis for lamellar refractive keratoplasty. He also emphasized the advantages of preserving the anterior membrane structure and developed methods and instrumentation for lamellar refractive procedures (Swinger and Chou, 1999). As mechanical microkeratomes were inaccurate with respect to tissue resection depths and caused inaccurate results, Peyman et al. (1989) proposed the use of laser energy to shape corneal tissue. Adopting the Barraquer and Peyman technique, Pallikaris et al. (1991) modified the bed under a corneal flap with an excimer laser rather than a microkeratome and named the procedure "laser in situ keratomileusis", now commonly known by its acronym,

LASIK.

1.9 Principles underlying LASIK

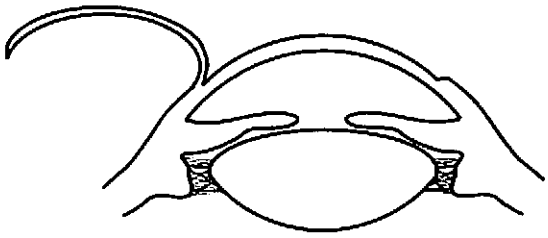
The main advantage of LASIK is that both the epithelial and Bowman's layers are preserved. Thus it reduces the risk of inflammatory and wound healing responses as the epithelium is still intact, acting as a barrier to bacteria from the external environment. In order to carry out laser photoablation to the stroma with preservation of epithelial and Bowman's layers, a superficial lamellar flap with a hinge is created. Then laser stromal ablation is carried out. After ablation, the corneal flap is re-positioned. Fig. 1.3 illustrates the principles of LASIK treatment.

1.10 Improved surgical technique

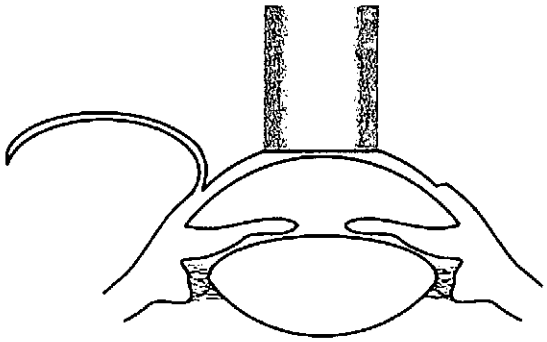
Previous versions of the microkeratome required manual advancement. The automatic microkeratome advances across the cornea without any assistance. Machat et al. (1999) stated that the advance rate of the microkeratome should vary between 0.75 mm/second and 3.7 mm/second. The stainless steel blade in the microkeratome oscillates at 8,000 to 20,000 cycles per minute.

Fig. 1.3. Principle of LASIK. (A) A corneal flap is created. (B) Laser ablation of the stroma. (C) The flap is re-positioned and the central cornea becomes thinner and flattened.

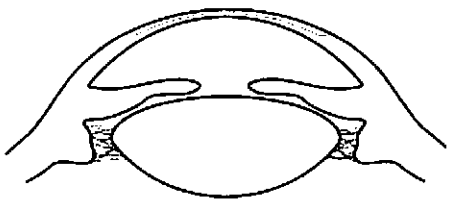
(A)



(B)



(C)



It is essential that the eye is directed toward the fixation beam and that it remains motionless during the procedure. An eye fixation device, the suction ring, is used during the flap opening. The suction ring will generate a vacuum suction holding the eye firmly in place and provide a rigid platform for the advancement of the microkeratome. Before the advancement of the microkeratome, Barraquer tonometry is carried out to ensure the intraocular pressure is sufficient high (greater than 65 mmHg) for advancement (Doane et al., 1996). The Barraquer tomometer has an inverted methacrylate cone of weight 10 g and superior convex surface radius of 22.15 mm. This magnifies the image obtained on the lower portion of the tonometer which is in contact with the cornea. The tonometer is designed so that when the applanated area of cornea is 3.8 mm, then the intraocular pressure is 65 mmHg. A reference circle 3.8 mm in diameter is marked on the tonometer head. An applanation circle smaller than the reference circle indicates that the intraocular pressure exceeds 65 mmHg.

The flap size created varies from 7 mm to 10 mm and the thickness is generally 160 μm. An adjustable microkeratome stopper is placed on the microkeratome to create a hinge in the corneal flap that helps secure the flap without sutures. There

are two common hinge positions, nasal and superior.

1.11 Ablation mathematics

Munnerlyn et al. (1988) derived a formula linking the depth of ablation (t), the dioptric power of correction desired (D) and the ablation diameter (d). The Munnerlyn formula is:

$$t = \frac{D \times d^2}{3}$$

The formula shows that each spherical equivalent dioptre of myopic correction performed using a 6 mm ablation diameter or zone requires ablation of 12 μm of tissue. The value of t is generally calculated initially on the basis of a 6 mm ablation zone diameter. If the value of t is satisfactory in the light of the corneal thickness, then the procedure goes ahead. If the corneal thickness is insufficient, then the calculation is repeated for a small ablation diameter. Machat (1996) suggested a technique called full "multimultizone" ablation that can minimize the amount of ablation needed. An ablation pattern distributed between 3.6 mm and 6.2 mm reduces the average stromal ablation to approximately 10 μm per

spherical equivalent dioptre. As the average central cornea thickness is approximately 550 μm and the flap thickness during the LASIK procedure is generally 160 μm, the average cornea will have 390 μm of posterior stromal bed left after the flap creation. The maximal myopic correction that can be performed on a patient with a 550 μm cornea using a full multimultizone technique is generally less than 14 D, while leaving a residual posterior stromal bed of 250 μm.

1.12 Complications of LASIK

Complications of LASIK include those of eye surgery in general, such as infection. Other complications which may occur are discussed below.

1.12.1 Intraoperative complications

1.12.1.1 Loss of, or inadequate, suction

This is a relatively serious complication that results in an abnormal cut of the corneal flap. The suction ring provides a stable platform for the microkeratome and it hardens the globe. If the globe is too soft, the blade cannot engage properly and an irregular cut results. Wilson (1998) stated that if the intraocular pressure is

too low during passage of the microkeratome, a thin or donut-shaped flap, usually small in diameter, is likely to be created. If this occurs, the irregular flap should be returned to its original position without laser ablation. Generally, surgeons prefer to carry out secondary treatment three months after the primary one (Augustine and Chester, 1996; Wilson, 1998).

1.12.1.2 Shaper head jams

Unusually, the microkeratome head may stop before clearing the desired diameter required for unhindered application of the laser. Under such conditions, application of laser ablation will result in corneal flattening near the hinge region and irregular astigmatism. Some surgeons will attempt manual extension of the flap (Wilson, 1998). Whitson et al. (1997) suggested that surgeons should allow several weeks for the cornea to heal before repeating the treatment.

1.12.2 Post-operative corneal complications

1.12.2.1 Epithelial growth in the interface

Epithelial growth within the interface is a potential complication of LASIK (Kezirian and Gremillion, 1995; Buzard et al., 1996; Lyle and Jin, 1996; Manche

et al.,1996; Manche and Maloney, 1996; Price et al.,1996). Epithelium may be introduced into the interface during the lamellar cut, or it may grow in from the peripheral surface epithelium. Epithelial tissue adheres to the blade and is then deposited within the interface during the passage of the blade. These cells may subsequently proliferate and produce a nest of tissue within the interface. If epithelial growth is found within the interface after LASIK, then treatment may be needed, depending on the extent and location of the tissue. If the epithelium within the interface continues to grow and threatens the pupil or induces irregular astigmatism, then the flap should be lifted and the epithelium removed (Wilson, 1998).

1.12.2.2 Infection

The risk of infection with LASIK is low because epithelial healing is rapid with creation of a corneal flap (Lyle and Jin, 1999). In case of infection, immediate culture is required and appropriate antibiotics should be used.

1.12.3 Post-operative optical complications

1.12.3.1 Induced irregular astigmatism

The complications mentioned above may result in irregular astigmatism, that is the two principal meridians are not at right angles to each other. However, other factors may also cause this. One major factor is that disparity between the stromal bed and the posterior surface of the flap will result in some degree of irregular astigmatism (Wilson, 1998). Another source of irregular astigmatism is irregularity of the excimer laser ablation on the bed. A central island is an example of irregular ablation (Slade et al., 1998). Consisting of a small steep area in the central cornea, a central island can occur as a result of a cooler central beam or irregular hydration during ablation with a central accumulation of fluid that masks the central cornea. A central island can be prevented by carefully wiping the central cornea to dry it or by additional ablation of the central 2.5 mm of the cornea. Faulty repositioning of the corneal flap or a thin cornea (less than 500 μm) may also induce irregular astigmatism (Lyle and Jin, 1996).

1.12.3.2 Overcorrection

Overcorrection was the most difficult to manage refractive complications of

refractive surgical procedures in the past, because it could not be treated. After LASIK treatment, about 10 to 20% of any overcorrection may disappear with time because of regression (Slade et al.,1998). If the overcorrection persists, hyperopic LASIK may be needed to correct it.

1.12.3.3 Undercorrection

Comparatively, undercorrection is easier to treat than overcorrection. It may due to inaccurate pre-surgical refractive evaluation, post-operative regression or development of a central island of corneal steeping after surgery (Lyle and Jin, 1999). When the refraction after the primary treatment is stable, a secondary treatment, known as enhancement, can be carried out to reduce undercorrection.

1.13 Previous studies of LASIK

1.13.1 Corneal nerve recovery after LASIK

Sensory innervation of the human cornea is derived from the ophthalmic and maxillary branches of the trigeminal nerve (Zander and Weddell, 1951; Ruskell, 1974). These bundles divide into two or three, bend 90 degrees, lose their Schwann cell sheath and penetrate Bowman's layer (Schimmelpfennig, 1982;

Müller et al., 1996). The basal epithelial or subepithelial nerve plexus between the basal epithelial cells and Bowman's layer is formed by the bending of these bundles, and fibers of this plexus send nerve terminals between the epithelial cells (Müller et al., 1997). Müller et al. (1996) also found that some keratocytes are innervated by stromal nerve fibers and both basal and wing cells are directly innervated by epithelial nerve fibers.

During LASIK surgery, the superficial stromal nerves are cut in the flap margin and the nerves in the stromal bed under the flap are exposed to excimer laser ablation. Only deep stromal nerve bundles under the flap, and the epithelial and anterior stromal nerves at the hinge of the flap, are spared (Linna et al., 1998). Linna et al (1998) investigated the morphological changes in rabbit corneal nerves after LASIK by using a histochemical acetylcholinesterase reaction. They found that there were cut nerve trunks at the wound margins and at the level of the flap interface in the stromal bed. There were losses of epithelial, basal epithelial or subepithelial and superficial stromal nerves three days after treatment. The numbers of regenerating nerves were increased and nerves were observed to emerge from the cut stromal nerve trunks at two and a half and at five months

after LASIK. Owing to the use of the hinged-flap technique, the LASIK procedure leaves some of the epithelial and stromal nerve intact in the flap near the hinge; thus corneal sensation is improved after LASIK compared with PRK and the remaining intact nerves help to restore the normal physiology, tear secretion and healing of the cornea.

1.13.2 Endothelium

There has been much work on endothelium changes after LASIK. Jones et al (1998) photographed the corneal endothelium before, two weeks after, and twelve weeks after LASIK with ablation depths ranging from 200 to 330 μm. Cell density and percentage of hexagonal cells were determined using 150 to 200 cells from each image. The mean pre-operative endothelial cell density was 2,549 (SD 365) cells per mm^2. There was no statistically significant change in the mean endothelial cell density at two weeks or twelve weeks after treatment. The investigators used a number of paired t-tests on non-independent data sets, thereby increasing Type I error, and it might have been more appropriate to have used repeated measures analysis of variance to compare the data sets. Jones et al. concluded that corneal endothelial cell density and morphology were unchanged 2

and 12 weeks after LASIK compared with pre-LASIK levels. Pérez-Santonja et al. (1997) and Kent et al. (1997) also found that LASIK causes no damage to the central corneal endothelium and that there is no significant loss of endothelial cells. These results are not surprising, because the laser beam in LASIK is focused on the stromal layer of the cornea and only stromal cells would be removed. Thus, although endothelial cells should not be damaged by LASIK procedures, Jones et al. (1998) have suggested that long-term follow-up studies over five to 10 years are needed to confirm endothelial safety after photorefractive surgery.

1.13.3 Intraocular pressure change after LASIK

Measures of applanation tonometry are influenced by corneal thickness and corneal curvature (Hansen and Ehlers, 1971; Mark, 1973; Ehlers et al., 1975; Johnson et al., 1978; Whitacre et al., 1993; Wolfs et al., 1997). Photorefractive surgery, for example LASIK, alters these corneal parameters and thus can change the accuracy of intraocular pressure (IOP) measurements by applanation tonometry. Fournier et al. (1998) found that there was a decrease in measured IOP following LASIK of 1.9 (SD 2.9) mmHg, and this may be due to the reduction of the corneal thickness or to the change in corneal curvature. Emara et al. (1998)

investigated IOP before and after LASIK and also found a reduction in measured IOP after treatment and suggested that central corneal thickness is an important variable in the evaluation of applanation IOP. Montés-Micó and Charman (2001) investigated the IOP after LASIK and PRK. IOP was measured before, and 12 months after refractive surgery, by both Goldmann applanation and non-contact tonometry. Surgery was carried out on one eye, the fellow un-operated eye being used as control. In accord with other investigators, they found that IOP, after both LASIK and PRK, decreased significantly in the treated eye but not in the control eye. The measured reduction in IOP after LASIK is therefore due, in whole or in part, to the reduction in corneal thickness and the curvature changes after surgery.

1.13.4 LASIK and contrast sensitivity

Contrast sensitivity testing was introduced by Schade in 1956, who suggested that it could provide much more information about vision than the usual visual acuity test (Schade, 1956). Visual acuity measured using standard clinical tests is useful but is an incomplete description of visual ability (Miller et al., 1972; Bailey and Lovie, 1976; Hess and Woo, 1978; Pérez-Santonja et al., 1998). Visual acuity tests determine the ability to resolve small details at high contrast, however, the visual

environment is composed of objects with a variety of spatial frequencies and contrasts. It is necessary to measure sensitivity to contrast as a function of spatial frequency in order to determine how well the visual system is performing in a complex environment. (Jindra and Zemon, 1989). Pérez-Santonja et al. (1998) evaluated the effect of LASIK on contrast sensitivity. Contrast sensitivity was tested pre-operatively and one, three, and six months post-operatively using the CVS-1000E contrast sensitivity unit (Vector Vision, Dayton). This test system provides four rows of sine-wave gratings, which at the recommended test distance of 2.5 meters test the spatial frequencies of 3, 6, 12 and 18 cycles/degree. Contrast sensitivity was decreased one month post-operatively, however the decrease was statistically significant only for spatial frequencies of 3 and 6 cycles per degree ($p=0.034$ and 0.030, respectively). There was rapid recovery of contrast sensitivity starting from the first month, and by the third month contrast sensitivity had returned to pre-operative levels.

Mutyala et al. (2000) used the CSV-1000 (Vector Vision, Dayton) which is basically identical to the CSV-1000E. Mutyala et al. found that contrast sensitivity was depressed at 6, 12 and 18 cpd for one week after LASIK, but had returned to

normal values one month post-operatively.

The results of these two studies were quite different. The refractive error range in the study of Mutyala et al. was from –1.25 D to –13.75 D, while that in the study of Pérez-Santonja et al. was –6.00 D to –19.50 D, and this may explain the earlier recovery time in the former study. It is difficult to explain why the subjects with the lower refractiver errors (those of Mutyala et al.) experienced depression in a wider range of spatial frequencies, and further study is needed to more fully characterize the changes in contrast sensitivity after LASIK.

1.13.5 Spectacle magnification before and after refractive surgery

Attention should be paid to the retinal image magnification change after LASIK treatment. Moving a myopic correction from the spectacle plane to the corneal plane induces a magnification of the retinal image. It is easy to calculate the magnification referenced to the pre-surgical eye because the axial length of the eye is unchanged. Using lens magnification formula (Rabbets, 1998) below, the change in size of the retinal image can be estimated.

$$LM = \frac{1}{1 - \frac{t}{nF_1}} X \frac{1}{1 - hF_v}$$

where t is the thickness of the lens; n is the optical index of the lens; F_1 is the front surface curvature of the spectacle lens; h is the distance from the back surface of the lens to the entrance pupil of the eye and F_v is the back vertex power of the lens.

For example, an –8.00D axial myope wearing trial frame correction with a vertex distance between 14 and 28 mm is corrected by refractive surgery. There will be 10% to 28% magnification induced, depending on the exact vertex distance of the trial frame correction. A 10% to 28% increase in magnification corresponds to an acuity increase between 2.1 and 5.4 letters respectively (Applegate and Howland, 1993).

Ideally, assume the treatment is prefect, no residual refractive error is left and no new optical aberrations are produced, visual functions, for example, visual acuity and contrast sensitivity, should be better than the pre-operative level. However, if image degradation occurs after treatment by the induction of new aberrations,

improvement of visual functions may not occur. The question is which parameters will give a dominant effect (Applegate and Howland, 1993).

1.13.6 Glare sensitivity after LASIK

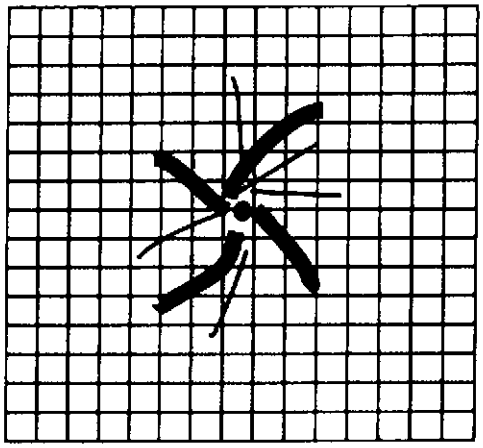
Sensation of glare is a common aftermath of LASIK especially at night, and may be due to corneal edema or to pupil dilation beyond the optical zone. Many authors have attempted to investigate light scattering and glare using different methods such as the Miller-Nadler glare tester, the Vistech MCT8000, the van den Berg Straylightmeter, and the Brightness Acuity Tester.

Elliott and Bullimore (1993) conducted a study to assess the reliability, discriminative ability and validity of the above glare tests. They found that the Miller-Nadler glare tester is poor at detecting subtle changes in the ocular media because of its large step sizes at low contrast thresholds. The Vistech MCT8000 also showed poor reliability, limiting its usefulness. Miller et al. (1972) suggested that a glare tester should include a large circular fluorescent dazzle glare source, and the targets should be black in color on a light background. They proposed that the background luminance should be altered by adding neutral density filters.

Paulsson and Sjöstrand (1980) investigated the glare effect of light scattered in ocular media. They measured contrast sensitivity with a bright light source, and found that contrast sensitivity decreased most at low and medium and less at high spatial frequencies. El Danasoury (1998) used a spot light test and questionnaire to examine the night glare effect after LASIK with different zone diameters. He asked the subjects to describe any glare, halos or distortion around the spot light, and to draw what they saw on an Amsler grid chart. Fig. 1.4 shows a sample result.

El Danasoury found that the use of a peripheral transition zone decreased night glare after LASIK compared with the single zone technique. The test used, however, did not fulfill the criteria proposed by Miller et al., and could not provide quantitative results. Perhaps because there is no universal glare tester for providing a reliable, sensitive and quantitative measure of glare, there have not been many quantitative studies of glare sensitivity after LASIK, and further work is needed here.

Fig. 1.4. Sample result of the glare test by El Danasoury. Re-drawn by the author from J Refract Surg 14: 512-516, 1998.



1.13.7 LASIK and corneal clarity

In photorefractive surgery, corneal tissues are ablated and a short-term corneal wound is formed. Research has shown that PRK has an effect on corneal clarity. Braunstein et al. (1996), using a scatterometer to measure corneal haze objectively and quantitatively, found that PRK increases corneal light scattering. The scatterometer consists of a modified slit-lamp microscope, with a fiber optic located at the image plane of the slit-lamp objective, a filter of 550 nm peak transmission and a 50 nm bandwidth interference filter for wavelength selection, and a photomultiplier detector (Jain et al., 1995; Jain et al., 1995; Braunstein et

al., 1996). Corneal haze levels were higher as ablation depth increased. Jain et al. (1995) used a scatterometer and rabbit eyes to compare the effect of PRK and LASIK on corneal light scattering. They found that PRK caused more corneal light scatter than LASIK. Wachtlin et al. (1999) found that LASIK caused less stromal reaction than PRK. Although these studies showed that LASIK causes less corneal light scatter than PRK, some corneal light scatter still occurs after LASIK treatment, and further study is needed to provide an objective and quantitative measure of corneal clarity.

1.13.8 Possible causes of reduction in visual performance after laser refractive surgery

Hersh et al. (2000) suggested six potential ways in which that refractive surgery might cause noise light (improperly focused rays, for example, aberrated rays) resulting in optical effects of glare or halos and reducing that reduce the visual performance. First, irregular corneal topography may result (Hersh, 1997; Abbas and Hersh, 1998). Second, residual and surgically induced astigmatism may occur. Third, decentration of the treatment zone, the edge effect and multifocality from the untreated cornea, would also increase noise light. Fourth, the dilated

pupil size under low illumination may allow more noise light enter to the eye. Fifth, corneal surface microirreularities induced by surgery would also produce noise light (Maguire and Bechara, 1994; Hersh et al., 1996). Sixth, corneal haze after surgery may also degrade the retinal image (Jain et al., 1995). Further study is necessary in order to assess more carefully the association of these factors and their relative clinical impact.

1.13.9 Optical aberrations and wavefront technology in LASIK

Aberrations are inherent to any optical system, and their complexity ranges from a simple shift in focus from the retina, to highly aberrated wavefronts which form distorted images on the retina. Refractive surgery, like LASIK, focuses on the correction of spherocylindrical errors as the most apparent and disturbing optical aberrations of the eye. However, these surgical procedures are accompanied by significant increases in higher-order optical aberrations (Holladay et al., 1991; Oilver et al., 1997; Martinez et al., 1998; Oshika et al., 1999; Selier et al., 2000; Mrochen et al., 2001). Holladay et al. (1999) examined corneal asphericity (the Q-value) and found that it changed from prolate (negative Q-value) to oblate (positive Q-value) after LASIK. This change will induce spherical aberration,

coma, astigmatism and distortion, which, because they are related to pupil size, will worsen in the dark, causing a consequential reduction in visual performance. Holladay et al. found that the change in functional vision after LASIK was indeed greater under lower levels of luminance and lower target contrast, suggesting they are caused by changes in asphericity. As surface irregularity, another possible cause of reduction in visual performance after refractive surgery, is independent of pupil size and light level (assuming the surface irregularities are uniform over the treated area of the cornea) it seems that the change in vision found by Holladay et al. was due more to a change in corneal asphericity than to a change in surface irregularity.

Refractive surgery then produces unwanted aberrations that will decrease vision quality, New technology has been directed towards avoiding aberration (MacRae et al., 1999). A customized ablation pattern is designed to eliminate all the significant aberrations of the eye. This kind of ablation requires accurate measurement of the aberration pattern of an individual's eye. As long ago as 1961 Smirnov described a subjective aberrometer, and this aberrometer has been used extensively in visual optic research in the past 40 years (Thibos, 2000). The

modern Hartmann-Shack aberrometer represents the technology advances made since Smirnov's work. (Liang et al., 1994; Thibos and Hong, 1999). However, wavefront-guided LASIK is still a new technique. Mrochen et al. (2001) found that it was not very predicable in reducing higher-order optical aberrations, and the technique still needs research and refinement.

1.13.10 Summary

Although a number of studies have been carried out to investigate the effect of LASIK on visual functions, there are still a number of functions which have not yet been fully characterized, such as contrast sensitivity, glare sensitivity and corneal clarity.

Chapter 2

LASIK in the Hong Kong Laser Eye Center

2.1 Introduction

In this chapter, the selection criteria applied by and the LASIK treatment procedures used in The Hong Kong Laser Eye Center (HKLEC) will be introduced. Also, the instrumentation used, the surgical room environment, and the follow up protocol will be described.

2.2 The Hong Kong Laser Eye Center

The HKLEC is a private eye surgery center providing refractive surgery and general eye examination. Appointments for LASIK are arranged according to the duty schedules of the ophthalmologists practicing in the Center. There is also an optometrist in the Center who carries out the preliminary and post-operative visual tests. There is a seminar room, two eye examination rooms and one surgery room in

the Center. LASIK patients will be assigned to a surgeon randomly if he or she does not have a preferred ophthalmologist. Three ophthalmologists were working in the Center during the timeframe of this study.

2.3 Pre-operative evaluation

2.3.1 Consultation and seminar

Clients who express an interest in LASIK are advised to attend a seminar session. The seminar is given by an ophthalmologist and covers details of the surgery, including principles, procedures, precautions, risk and expected visual outcomes. Auto-refraction and Orbscan pachometry is then carried out in order to ensure that the corneal thickness of the client is sufficient with respect to the refractive error. Individual consultations will then be carried out by the ophthalmologist.

2.3.2 Visual assessments

If applicable, the prospective patient will be requested to stop contact lens wear, one week for soft contact lenses or three weeks for rigid lenses, before further examination. A comprehensive eye examination will then be carried out. During the examination, other information regarding the prospective patient, for example,

ocular and general health history, occupation and visual needs will be collected. Subjective refraction will be carried out by the optometrist and the end point of the test is standardized according to Brown and Yap (1995) (please refer to Appendix for details). The best corrected visual acuity will then be obtained. After subjective refraction, corneal topography and corneal thickness will be measured using the Orbscan (Orbtek, Inc, USA). Also, the size of pupil under scotopic and photopic conditions will be measured using a PD ruler. Finally, cycloplegic refraction will be carried out.

2.3.3. Ocular health assessment

After the visual assessment has been completed, the ophthalmologist will carry out an ocular health examination. The aim of the examination is to detect any ocular disease or anomaly that may result in a poor prognosis for LASIK. The process below is carried out in HKLEC to confirm suitability for LASIK and to collect data required prior to surgery.

- Consultation and seminar
- Ocular and general health history
- Contact lens history

- Best corrected visual acuity
- Pupil size in dim and normal light conditions
- Subjective refraction
- Corneal topography and pachometry
- Cycloplegic refraction
- Clinical assessment of cornea
- Clinical assessment of retina

2.4 Patient selection criteria

Patients must be over 18 years old, have undergone all the visual assessments shown above and the sufficient corneal thickness for ablation with respect to the refractive error. Patient should not have any of the following contraindications.

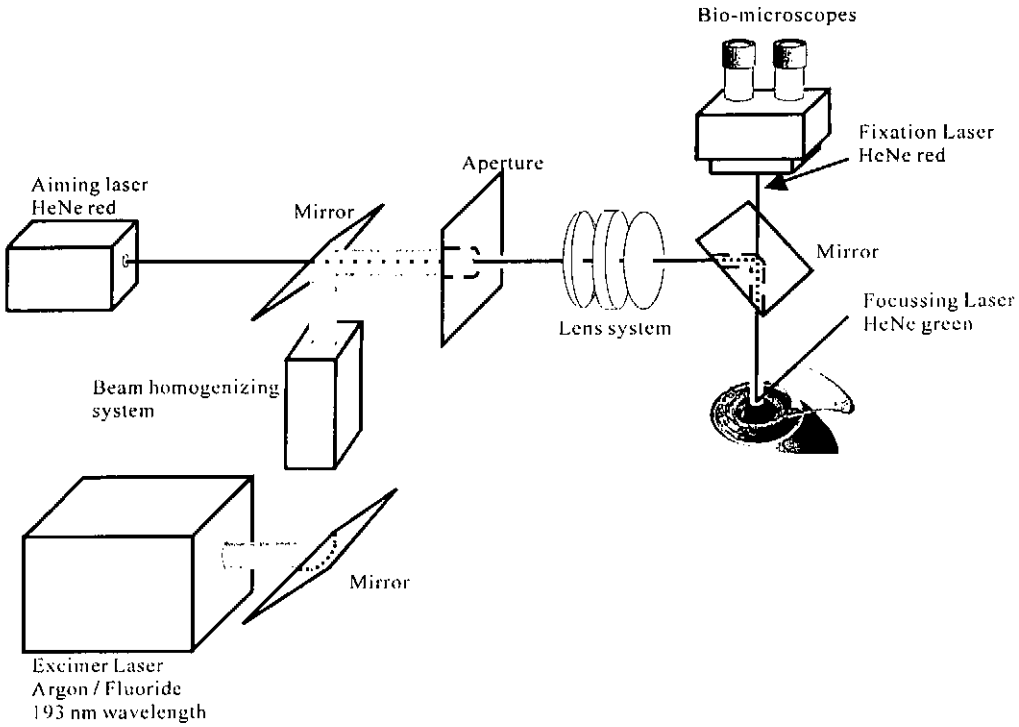
- keratoconous
- blepharitis
- herpes simplex keratitis
- monocular status
- retinal degeneration
- autoimmune disease

- any medical contraindication, for example pregnancy, uncontrolled diabetes mellitus.

2.5 The instrumentation for LASIK used in the HKLEC

The Excimer-Laser-System, Technolas 217 C-Laisk developed by Chiron Technolas is used for LASIK surgery in HKLEC, the same instrument being used for all LASIK procedures carried out.

Fig. 2.1. A schematic diagram of the tower unit of the LASIK machine. Redrawn from the manufacturer's manual.



2.5.1 The Excimer-Laser-System

The system comprises the following parts.

2.5.1.1 Surgical microscope

The operator can view the patient's eye with the help of a binocular microscope.

2.5.1.2 Tower unit

The tower unit houses the optical beam guiding system and auxiliary lasers (see Figure 2.1). The laser beam passes through various lens systems such that a high-energy, homogeneous laser beam becomes available for the refractive surgery. The auxiliary lasers include aiming laser, fixation beam and focusing laser. The aiming laser is a red diode laser coupled coaxially with the treatment beam for the operator to watch the position of the excimer beam. The fixation beam serves as a fixation point for the patient and is situated in the surgical microscope. The focusing laser is used to fix the position of the eye so that the focusing point of the treatment beam is located on the surface of the cornea and in the center of pupil.

2.5.1.3 Emergency-off switch

This switch turns off the whole system in case of an emergency.

2.5.1.4 Electrical rack

This is where the computer and monitor are located. The whole system is computer-controlled.

2.5.1.5 Containment basic unit

This unit contains the laser light source and gas supply system for laser emission.

2.5.1.6 Foot switch

This triggers the firing of the laser beam.

2.5.1.7 Operator control console

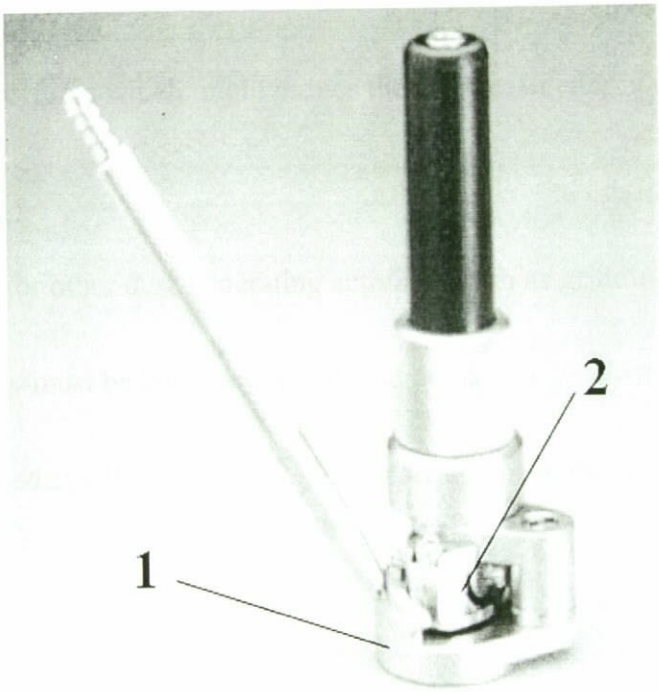
The controls on the console include an on/off switch for the auxiliary lasers, a brightness regulator for the fixation light source and a joystick to adjust the patient bed.

2.5.1.8 Patient bed

The patient will rest on the bed during treatment.

2.5.1.9 Corneal shaper

Fig 2.2. The automatic corneal shaper comprises (1) a suction ring and (2) a gear-driven microkeratome (Chiron Vision, Germany).



2.6 Surgery room

The room where the surgery takes place is an important factor affecting the performance of the LASIK machine, and thus the outcome of the treatment. The laser room must fulfil the following requirements (Chiron Technolas, 1996):

1. Since vapors of solvents and cleaning liquids can damage the optical components and can impair the laser system's performance, sufficient

ventilation must be possible.

2. An air filtering device is needed.

3. No humidifiers or air sterilization devices are allowed in the room.

4. Neither the patient nor any member of staff in the room should wear any cologne or perfume which might reduce the amount of energy delivered to the cornea.

5. No smoking or other dust-generating activities such as grinding are allowed.

6. The humidity must be kept between 30 and 50 %

LASIK procedures in the HKLEC are all carried out in the same room.

2.7 Surgical procedures

2.7.1 Drugs used

Table 2.2 shows the drugs used in the HKLEC before and after LASIK treatment.

Table 2.2. Drugs normally used before and after LASIK treatment in the present study.

Drugs	Nature of the drugs
Voltaren (tablet or eye drops)	Nonsteroidal anti-inflammatory drug (NSAID), used to treat symptoms of inflammation of the eye and pain management
TOBRADEX® (eye drops)	Tobramycin and dexamethasone ophthalmic ointment is a sterile, multiple dose antibiotic and steroid
FML®	Sterile, multi-dose topical ophthalmic suspension containing the corticosteroid, rimexolone
TARIVID®	Broad and medium spectrum antibiotic
Tears Naturale ®	Lubricant eye drops

2.7.2 Photo-documentation

The surgical procedures in HKLEC are basically the same as mentioned in Chapter 1. The photographs shown in Fig. 2.3 document the procedure and were taken in the HKLEC.

Fig 2.3a. Speculum applied to the eye to hold the lids wide apart.

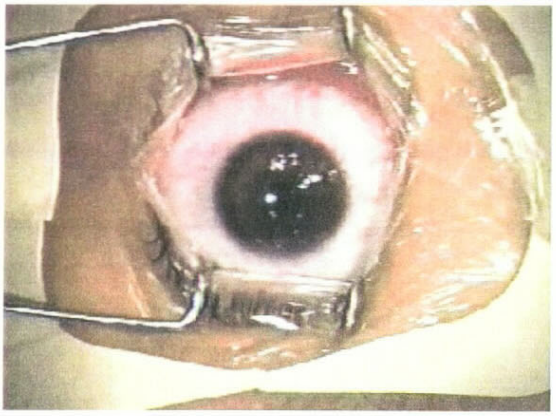


Fig 2.3b. Marker impregnated with ink marking the cornea

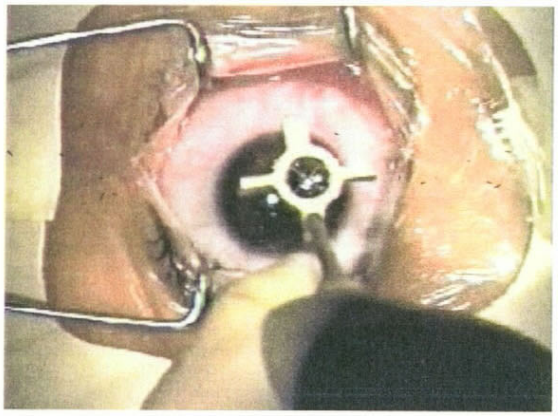


Fig 2.3c. The suction ring is applied

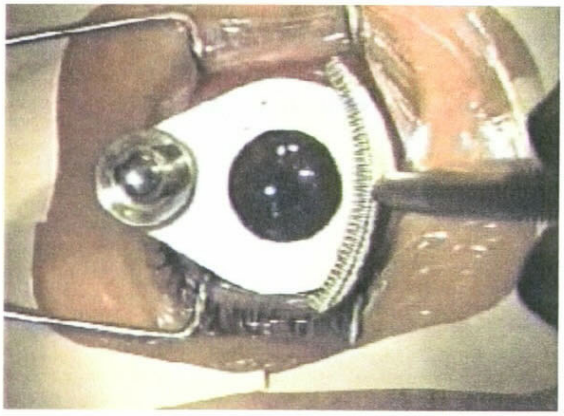


Fig 2.3d. Checking for adequate pressure using a Barraquer tonometer

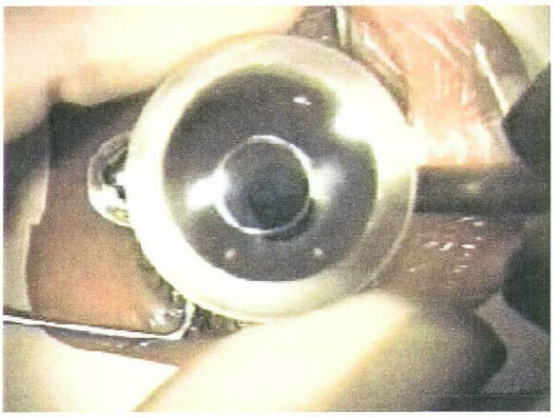


Fig 2.3e. The microkeratome is applied and ready for advancement

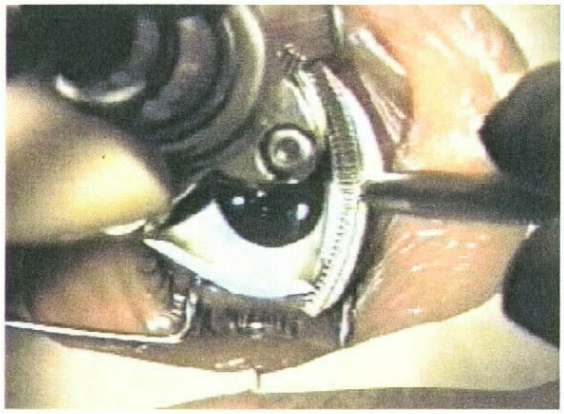


Fig. 2.3f. Opening the corneal flap with a spatula

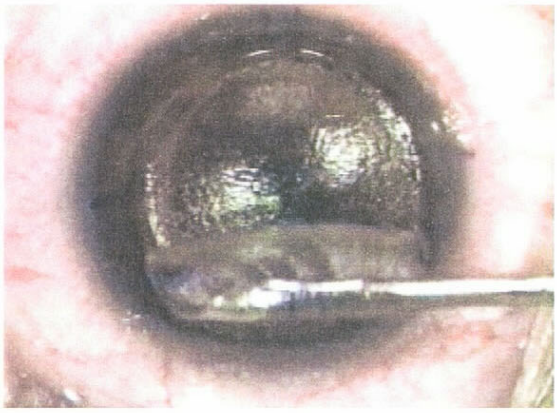


Fig. 2.3g. Wiping the stroma with a surgical sponge in order to remove debris

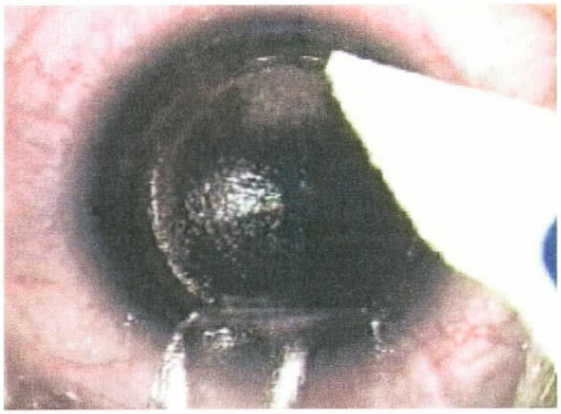


Fig 2.3h. An aluminum plate is used to cover the opened flap preventing from rebound during ablation. The laser is ready to fire.

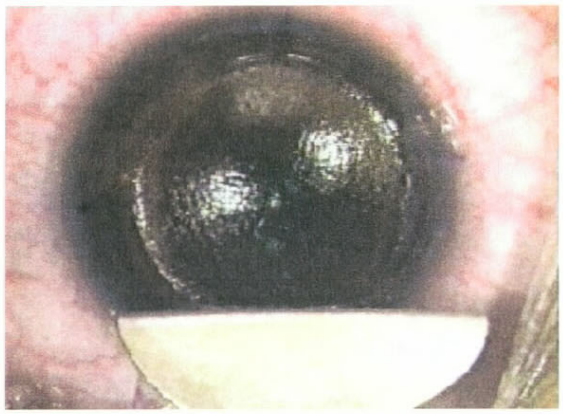
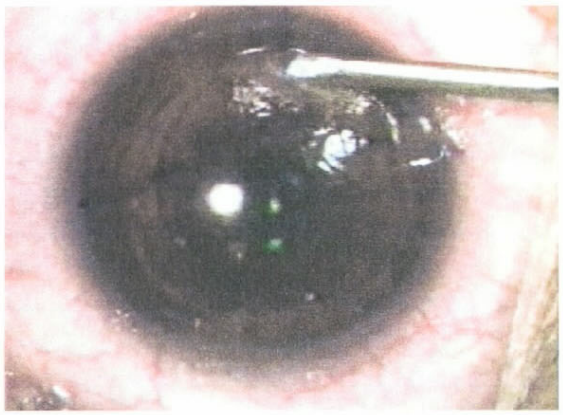


Fig.2.3i. Closing the flap with a spatula after ablation



2.8 Post-operative review schedules in HKLEC

Patients are requested to have review visits after LASIK treatment, typically according to the following schedule:

- One day after treatment
- One week after treatment
- One month after treatment
- Three months after treatment
- Six months after treatment
- One year after treatment
- Annual regular check thereafter

  Patient are asked to come back immediately if they experience eye discomfort or reduction in vision.

During review visits the following visual assessments will be carried out:

- Unaided visual acuity (carried out by optometrist)
- Best corrected visual acuity (carried out by optometrist)
- Subjective refraction (carried out by optometrist)
- Clinical corneal assessment (carried out by ophthalmologist)

2.9 Subject recruitment

Subjects in the present study were recruited with the help of the staff in the Center. Details of the study including the aims, procedures and subject's rights were given to all the patient, and an Information Sheet (Appendix 5) was given to any patient who expressed interest in participating. There was no selection by the medical staff in the center, however, self-selection by the patients might have occurred. Patients who were busy might not participate in this time-consuming study because it involved repeated measurements throughout the year. The subject samples, therefore, may be biased towards individuals with more time, for example, housewives. This probably explains why there were more female than male subjects. This bias, however, is unlikely to affect the results. The numbers of subjects recruited for the LASIK experiments described in this thesis are summarized in Table 2.3. Loss to observation was mainly due to the long duration of the tests.

Table 2.3. The number of LASIK subjects recruited.

Experiment	Number of subjects		
	Recruited	Withdrawal	No show in visits
2	52	7 (13.46%)	4 (7.69%)
4	25 (from Exp 2)	4 (16%)	0
6	25	0	1 (4%)

2.10 Summary

The Hong Kong Laser Eye Center is a private practice providing LASIK, photorefractive surgery. Prospective LASIK patients must undergo a series of visual assessments to ensure suitability for this surgery. The surgical procedures used in the Center are widely accepted and adopted by ophthalmologists around the world. LASIK patients are followed closely after treatment.

Chapter 3

Contrast sensitivity before and after LASIK

3.1 Introduction

This chapter describes an experiment to determine the change of a visual function, contrast sensitivity, after LASIK treatment. Two contrast sensitivity testing protocols were compared and the reliability of the finally selected protocol was found. Subjects who were patients of the HKLEC were tested prior to LASIK and then followed up for one year post-LASIK.

3.2 Experiment 1

Reliability of 2-Alternative Forced-Choice and Yes-No methods of measuring contrast sensitivity function

3.2.1 Objective

The objective of this study was to compare the reliability (repeatability) of the contrast sensitivity test methods, 2-alternative forced-choice (2AFC) and Yes-No (Y-N). The software PSYCHO 3.0 for Windows was used in both cases. The more reliable method was subsequently used in Experiments 2, 3 and 4.

3.2.2 Introduction to the two test methods

3.2.2.1 Two-Alternative Forced-Choice (2AFC)

This test uses two positions on the computer monitor, left and right, for presentation of the stimuli. The program presents each step (spatial frequency) in one of two target positions and the subject indicates on which side the stimulus is seen. The subject is forced to make a decision as to where he or she thinks the stimulus is, or if the stimulus cannot be seen, to guess. If the subject makes no response, or fails to respond in time, the next step is shown and the current step is shown again at a later

stage. For the next sequence (the number of times that a grating of a given spatial frequency will be displayed), the control variable (contrast in this case) is changed for each step according to the chosen staircase.

3.2.2.2 Yes-No (Y-N)

In the Y-N method, the program presents each step in turn and the subject responds "yes" if he or she can see the stimulus and "no" if he or she cannot see it. If the subject makes no response, or fails to respond in time, the step is presented again immediately if steps are being shown in an ordered sequence, or later if the order is randomized. This continues until a response has been recorded for every step in the sequence and the contrast or other control variable is changed for each step, according to the chosen staircase procedure.

3.2.2.3 Fixed-step-size (FSS) staircase

A forced-choice staircase with a fixed step size is commonly used in visual detection tests. García-Pérez (1998) analyzed the step size protocol used in papers published in Vision Research and in the Journal of the Optical Society of America A from 1994 to 1996, and found that psychophysicists preferred the

fixed step size (FSS) staircase method. Eighty-two out of 120 papers used this kind of staircase. García-Pérez recommended that attention should be paid to the design and the description of the FSS staircase. He stated that large steps should be used in order to produce reversals more quickly, allowing for longer staircases without incurring more trials. Moreover, if the staircase sinks below threshold after a sequence of guesses, large steps allow for a quick come-back to the range of contrasts for which the stimulus is perceptible, thus providing subjects with reminders of what the stimulus looks like. García-Pérez also suggested that a smaller step down than up should be used. Equal size for the steps up and down imply that the psychometric function will not be appropriately sampled. Unequal step size solves this problem and if the step down is larger than up, the staircase will sink in the low end of the function.

García-Pérez suggested a series of appropriate ratios of the size of the step down to up. The ratios are 0.2845, 0.5488, 0.7393 and 0.8415, for the one-, two-, three-, and four-down/one up rules respectively. That is, how many consecutive correct responses are required to move one step "down" and how many consecutive wrong responses are required to move one step "up". The present study adopts

this suggestion, and in both of the CSF tests carried out the staircase was set to two-down/one up. The step up size was 8dB and the step down size was 5dB. The ratio is 0.625, close to the recommended ratio of 0.55.

3.2.3 Methods

3.2.3.1 Equipment

Computer

Hardware:	Pentium MMX, 233MHz computer
	High-resolution video display unit (VDU) for subject. The VDU is a 20" flat profile CRT color monitor with multi-frequency scanning 31-105kHz horizontally.
	Standard CRT monitor for the examiner to control the test
	Cambridge Research Systems Visual Stimulus Generator (VSG2/3).
	Cambridge Research Systems CB3 Response Box input device
Software:	Cambridge Research Systems PSYCHO Windows.
Optical:	Trial-frame and trial-lens set

3.2.3.2 Instrumentation - Software

The staircase technique with 4 reversals was used for target presentation. There were ten steps in both tests. In the Y-N method, there were fifteen sequences in each

step, while in the 2AFC method there were twenty sequences. The spatial frequencies used were 0.3, 0.81, 1.52, 3.42, 5.1, 6.84, 8.2, 10.27, 13.7 and 20.53 cpd. The thresholds of the results of the staircase were determined by averaging the reversal values. Each screen shot of the grating was displayed for three seconds including one second "attack time" (the time taken for the mean luminance of the target to reach the test level), and one second "decay time" (the time taken for the mean luminance of the target to return to screen luminance). A control step of spatial frequency 2.0cpd with super-threshold contrast was displayed for 20% of the presentation, to keep the subject alert.

3.2.3.3 Instrumentation – CB3 Response Box

The CB3 Response Box is an input device linked to the VSG board by a parallel port and a three meter cable. It has three switches, A, B and C, and the functions of the switches are assigned by the software. In the 2AFC mode, the three buttons, A, B and C represent the left target, no function and the right target respectively. In the Y-N mode, A represents "Yes" and C represents "No". There is a beep sound when a new target is displayed and a beep sound when the input signal from the subject is confirmed.

3.2.3.4 Environment

Dim room lighting was used to reduce reflection from the VDU. The examiner's monitor is not visible to the subject during measurement in order to reduce the glare to the subject. The target VDU was placed one meter in front of the subject at his or her eye level.

3.2.4 Subjects

Ten subjects, three naïve observers and seven observers experienced in psychophysical measures, with best corrected visual acuity of logMAR 0.0 or better, free of ocular disease and with clear ocular media, were recruited.

3.2.5 Procedure

1. The cornea of the subject was examined under slit-lamp and the crystalline lens was examined by direct ophthalmoscopy. The subject was rejected if any corneal scar, edema or cataract was visualized.
2. Subject was informed about the study verbally and via an information sheet (Appendix 5) and was given the opportunity to ask questions.
3. A consent (Appendix 6) form was signed before the subject was admitted to

the study.

4. The subject, wearing the trial lenses for the best correct visual acuity, sat one meter in front of the VDU.
5. The Y-N and the 2AFC tests were carried out binocularly and the order of the tests was randomized by asking the subject to draw a card from 2 with the names of the tests printed on them.
6. A fixation target (a small black cross) was positioned at the center of the VDU to help the subject fixate during the tests.
7. In the 2AFC method, the subject was asked to push switch A if the grating was seen in the left of the screen, to push switch C if the grating was seen in the right and to guess if he or she could not identify which side the grating was on.
8. In the Y-N method, the subject was asked push switch A if he or she could see the grating and to push switch C if he or she could not see it.
9. A short break was given during the test if requested by the subject.
10. A five minutes break was given after each test. Then both of the tests were repeated.

3.2.6 Results

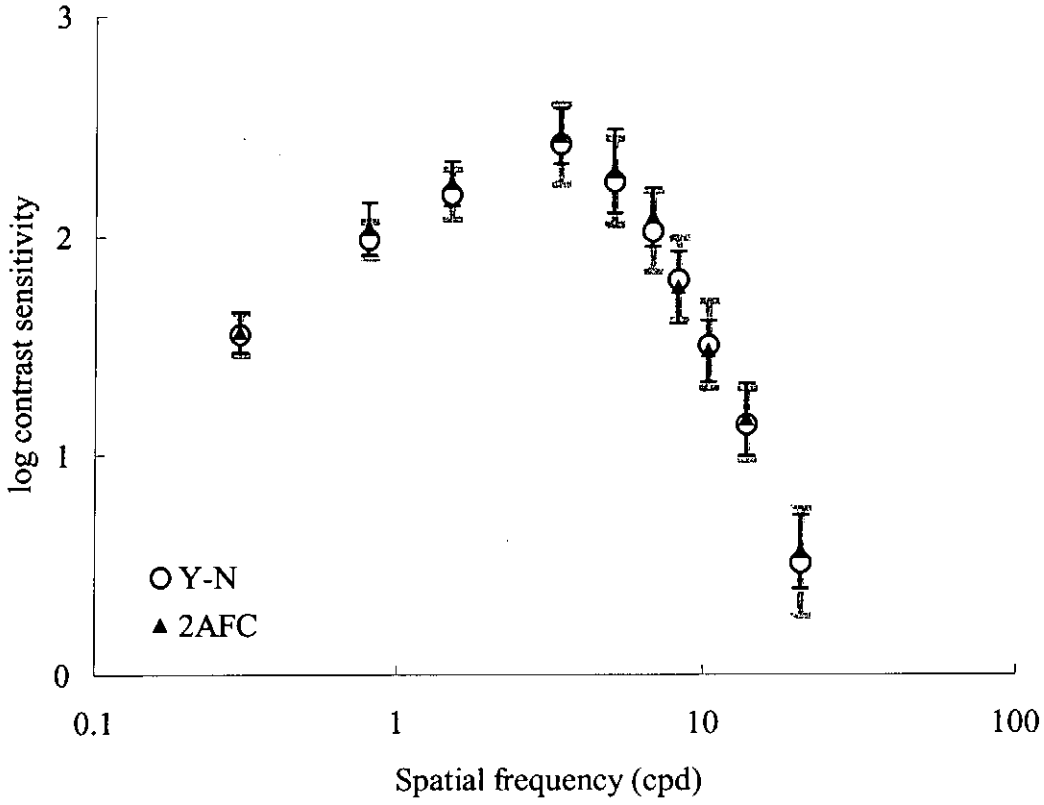
The standard deviations of the mean difference in the contrast sensitivity for all spatial frequencies between the first and second test using the Y-N method and 2AFC method were 0.0508 and 0.0501 log units respectively. The mean contrast sensitivity for each spatial frequency examined and for each method is shown in Fig 3.1. The numerical data are given in Appendix 4. The repeatability was expressed by the standard deviation of the mean difference in the contrast sensitivity for all subjects for all frequencies multiplied by 1.96. The repeatability of the Y-N method was 0.0995 log unit. In 2AFC, it was equal to 0.0981 log unit.

3.2.7 Discussion

3.2.7.1 The repeatability values

The repeatability values are very close for the two test methods. In both tests, an individual change can be assumed to be real if it is greater than 0.1 log contrast unit.

Fig. 3.1. The mean contrast sensitivity functions curves measured by Y-N and 2AFC methods (n=10). The error bars show 1 SD.



3.2.7.2 Y-N method Vs 2AFC method

Although the repeatability values of the two test methods are similar, the Y-N method required fewer sequences to provide a result than 2AFC method. The subjects were asked which test they found more interesting. Eight out of ten subjects preferred the Y-N method. Under these circumstances, the Y-N method was selected for use in the other experiments in the present study.

3.2.7.3 Design of the test

In designing a psychophysical test, concerns are not only the accuracy and the reliability of the test, but also the duration. It is true that the greater the number of reversals in a staircase the more accurate the result, and ideally a psychophysical test should use thousand of steps. However, subjects may find difficulty concentrating on the task if the stimuli are uninteresting. Moreover, it will be difficult to persuade subjects to participate, especially when a study involves repeated measures. Under these circumstances, the selected psychophysical test is a compromise between the duration and the accuracy of the test.

3.2.7.4 Number of sequences

The number of spatial frequencies used was ten. In the Y-N method, there were fifteen sequences for each spatial frequency. Therefore, the subject was requested to respond 150 times (maximum number of response). In the 2AFC method, there were twenty sequences for each spatial frequency, and the subject made 200 responses (maximum). The numbers of sequences, fifteen and twenty, were determined by a trial and error process carried out prior to subject testing. In the Y-N method, fewer than ten sequences did not result in a typical contrast

sensitivity function curve (inverted U sharp, contrast sensitivity reaching a peak at about 3 to 6 cpd and gradually decreasing at both lower and higher spatial frequencies). Twelve sequences resulted in a typical CSF curve and increases in the number of sequences beyond fifteen resulted in little change in function. It was therefore decided to use fifteen sequences for the Y-N method in the present study. At least twenty sequences were needed using the 2 AFC methods in order to obtain similar results to those found by the Y-N method.

3.2.7.5 The spatial frequencies used

Spatial frequency depends on the viewing distance. The spatial frequency of a 20 cpd grating viewed at one meter will be doubled when viewed at two meters. The dimensions of the examination room for Experiments 2 and 4 meant that spatial frequencies higher than 20.53 cpd could not be generated. The tests cover a range from a low spatial frequency of 0.3 cpd to a high spatial frequency of 20.53 cpd, the latter being the highest spatial frequency that the VSG can generate at one meter viewing distance.

Originally the spatial frequencies 0.3, 0.8, 1.5, 3.4, 5.1, 6.9, 8.2, 10.3, 13.7 and

20.5 cpd were tested and the duration of the process was about twenty minutes. At the end of the test subjects were asked their opinion about duration. All complained about its excessive length. Most were experienced in psychophysical measures, and naïve observers are even more likely to find the process tedious. Therefore, the number of steps was decreased from ten to seven, spatial frequencies of 5.1, 8.2 and 13.7 cpd being deleted from the test in Experiments 2, 3 and 4.

3.2.7.6 Sampling theory and aliasing

In order to distinguish two individual dark and light bars in a grating stimulus, there must be at least two sample points per cycle of grating (D'Zmura, 1996). Oversampling occurs if the neurons on the retina are so tightly packed that the requirements of the sampling theory are exceeded. However, if the neurons are too widely spaced to satisfy the theory, undersampling occurs. During undersampling, information from the stimulus will be lost and this may cause the neural image to misrepresent the stimulus as a pattern of lower spatial frequency. This misrepresentation due to undersampling is called aliasing. Such an undersampling will not only lower the perceived spatial frequency, but also

misrepresent the orientation of the stimulus pattern as well as the direction of movement if the stimulus is moving. This misrepresentation in drifting direction of the aliased pattern is called "motion aliasing" (Thibos, 1998).

Miller et al. (1996) examined the cone spacing using the average power spectrum technique. They found that the smallest resolvable cone spacing is about 3.0 μm, which corresponds to a cone mosaic sampling frequency of about 100 cpd. This extremely high density of cones causes the Nyquist frequency to be higher than the optical cutoff of the eye. Campbell and Green (1965) suggested that the optical system of the eye has a low-pass spatial-filtering action such that aliasing will not normally occur in foveal vision. There is evidence that aliasing occurs everywhere in the visual field except the central few degrees (Williams, 1985; Williams and Coletta, 1987; Galvin and Williams, 1992; Wang et al.,1997).

In the present study, most of the subjects in Experiment 1 commented that they sometimes saw oblique or wave-like gratings in the periphery of the screen while they were looking at the central fixation target. This is likely to be due to the aliasing effect mentioned above, and occurred for medium and high spatial

frequencies. Thibos et al. (1996) found that aliasing occurred even for an intermediate spatial frequency target, a 5.5 cpd grating, when it was 20 deg off the fixation axis. Aliasing in the periphery of the VDU screen may not affect the result of the experiment, since central vision is being examined, however any visual disturbance to the subject should be eliminated if possible. Therefore, the VDU screen was modified by adding a mask with a 0.26 m aperture that reduced the visual angle at one meter to about 14.8 deg.

3.2.8 Conclusion and summary

Objective (repeatability value) and subjective (subjects' preference) considerations were taken into account in selecting the Y-N method for testing CSF in Experiments 2, 3 and 4 in the present study. The steps used were 0.3, 0.81, 1.52, 3.42, 6.84, 10.27, and 20.53 cpd, fifteen sequences being used in each step. The staircase of the test was set to two-up/one down, the step up size was 8 dB and the step down size 5 dB with 4 reversals. A 0.26 m aperture was used to mask the VDU. The repeatability value of the test was about 0.1 log contrast unit.

3.3 Experiment 2

Contrast sensitivity before and after LASIK

3.3.1 Introduction

Normal visual acuity does not mean an individual performs normally on all visual tasks. Acuity is a poor predictor of visual performance in certain daily perceptual tasks such as face perception (Sekuler et al., 1982). It suffers from a number of limitations, for example, it reflects the behavior of only the central 1% to 2% of the entire visual field. It also represents just the ability to resolve fine detail. Moreover, it can be insensitive to subtle changes in the status of the visual system because of its high contrast. In order to investigate more subtle changes, other aspects of vision should be measured and contrast sensitivity is one such aspect. Sekuler (1974) and Bodis-Wollner et al. (1980) stated that contrast sensitivity represents visual sensitivity to a wide range of target sizes and luminance, and contrast sensitivity test has been proven to be useful in detecting visual disorders that have evaded detection by the usual acuity tests. Regan et al. (1977), for example, used it to diagnose the visual loss in multiple sclerosis.

3.3.2 Objectives

The objective of this part of the study was to evaluate the effect of LASIK on contrast sensitivity. Measurements were done before and after LASIK treatment and subjects were followed for a year after the treatment. The contrast sensitivities before and after LASIK were then compared.

3.3.3 Method

The equipment used was as described in section 3.1.3 in Experiment 1. In this experiment, the Y-N method and seven spatial frequencies, 0.3, 0.8, 1.5, 3.4, 6.9, 10.3 and 20.5, were used. The room luminance was adjusted to a level close to the mean luminance of the VDU when the contrast sensitivity grating was generated. The VDU was positioned one meter in front of the seated subject, and at eye level.

3.3.4 Subjects

Fifty-two subjects volunteered to participate in this part of the study. Forty-one subjects completed the experiment. Twenty-four were female and seventeen male. Their mean age was 31.71 (SD 4.86) years and their mean spherical equivalent refractive error (SERE) was –6.03 (SD 2.28) D. See Appendix 2 for further details

of refractive error. All subjects were LASIK patients of the HKLEC and had met the patient selection criteria employed by the Center (Chapter 2).

3.3.5 Procedure

1. An information sheet (Appendix 5), detailing the procedure to be carried out, was given to the subject. The procedures were also explained verbally and the subject given an opportunity to ask questions.
2. A consent (Appendix 6) form was signed before any tests were carried out.
3. Testing was carried out before any diagnostic or therapeutic drugs were applied in the course of the ophthalmological examination carried out by the refractive surgeon.
4. The procedures used for visual acuity and refractive error measurements were as described in Appendix 1 and Appendix 2.
5. The subject, wearing clean trial lenses for best visual acuity, sat one meter in front of the VDU.
6. The contrast sensitivity test was normally carried out on the right eye except that in the case of subjects undergoing LASIK only on the left eye, that eye would be tested.

7. The subject was asked to press button A on the CB3 Response Box if he or she could see the grating and to press button C if he or she could not see it.
8. A break was given to subject during the test, upon request.
9. Measurement was carried out according to the following schedule, pre-operation, one week, one month, three months, six months and one year after the treatment. Appointments were made at the subjects' convenience, at no particular time of the day.

3.3.6 Statistical tests

Data were analyzed using repeated measure ANOVA (RM ANOVA) and Pearson's coefficient correlation.

3.3.7 Results

3.3.7.1 Change in contrast sensitivity

There were depressions of the contrast sensitivity for all individual spatial frequencies after LASIK (RM ANOVA, $p<0.01$ for all individual spatial frequencies)

Fig. 3.2a shows the mean contrast sensitivity function curves of the 41 subjects. Fig. 3.2b focuses on the changes in log contrast level of individual spatial frequency. All the contrast sensitivity levels decreased after LASIK treatment and returned gradually to pre-LASIK levels. The numerical data are given in Appendix 4.

In post-tests, the contrast sensitivity values before treatment (baseline) were compared with the values found at different post-operative visits (1 week, 1 month, 3 months, 6 months and 1 year). Statistically significant differences were found for all pairs of measures ($p < 0.001$) except for baseline and 1 year after treatment ($p > 0.05$).

Fig. 3.2a. The mean contrast sensitivity for the spatial frequencies tested at different visits (n=41). y-axes are the log contrast sensitivity and x-axes are the spatial frequencies in cycle per degree. The error bars show 1 SD.

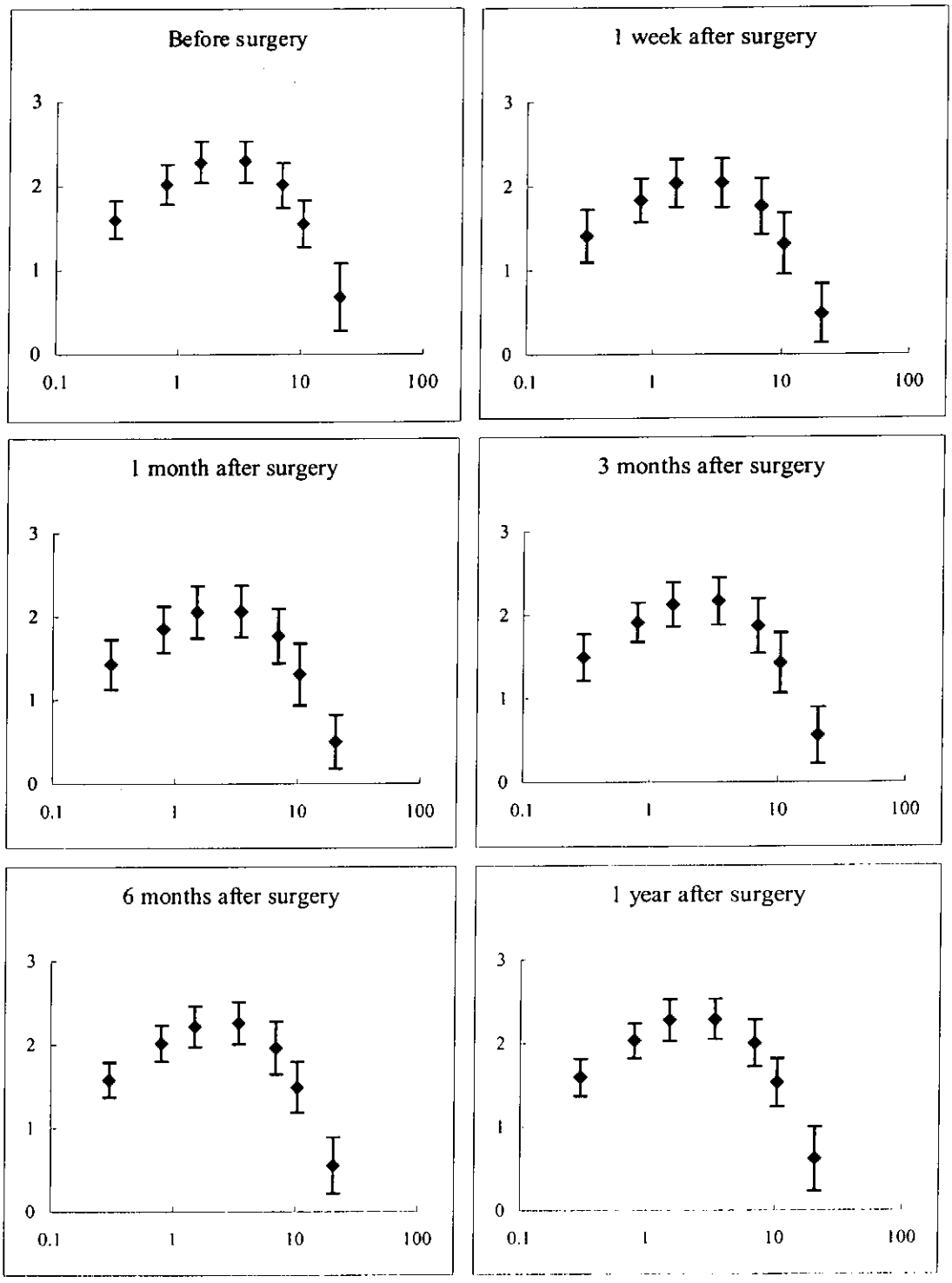
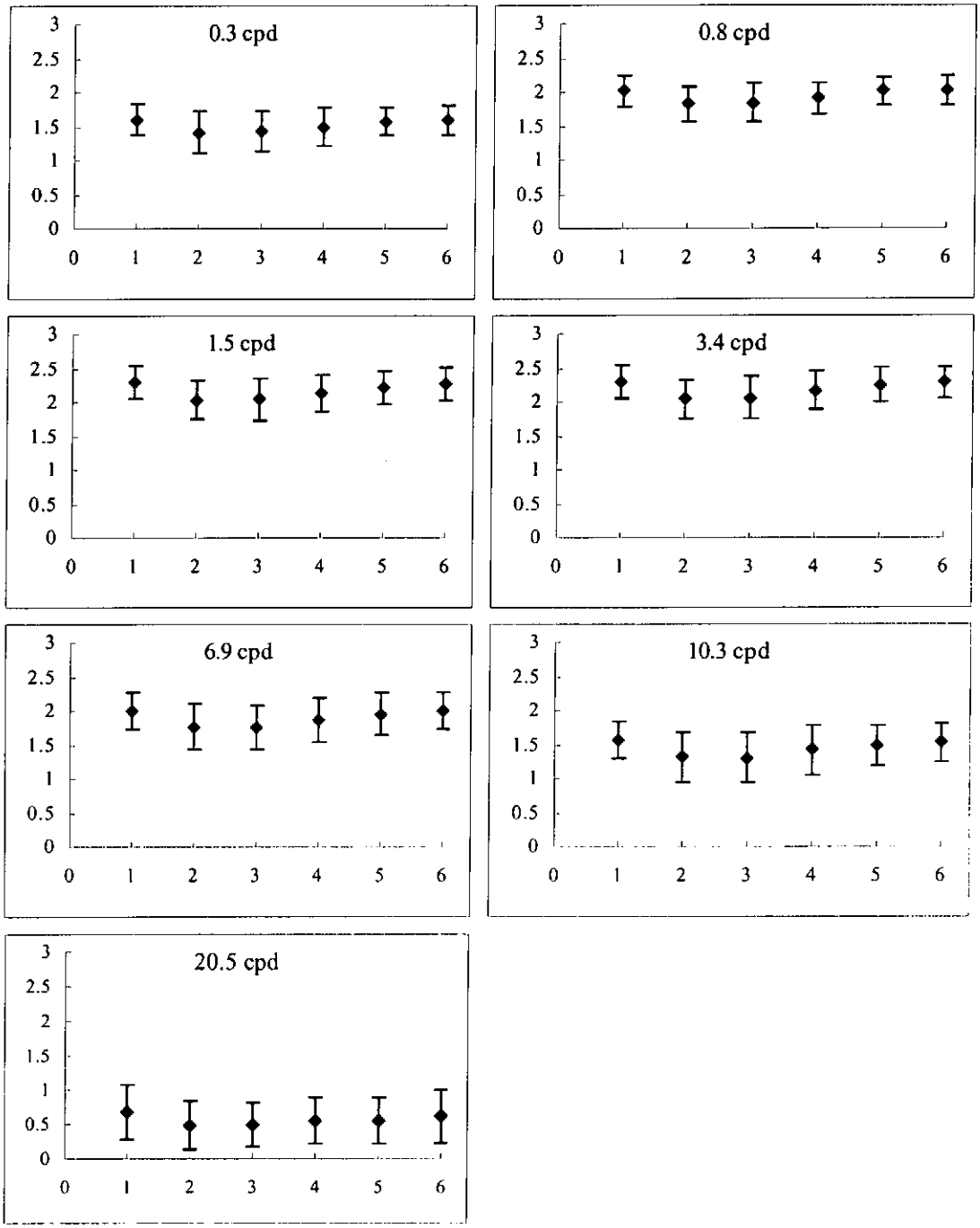


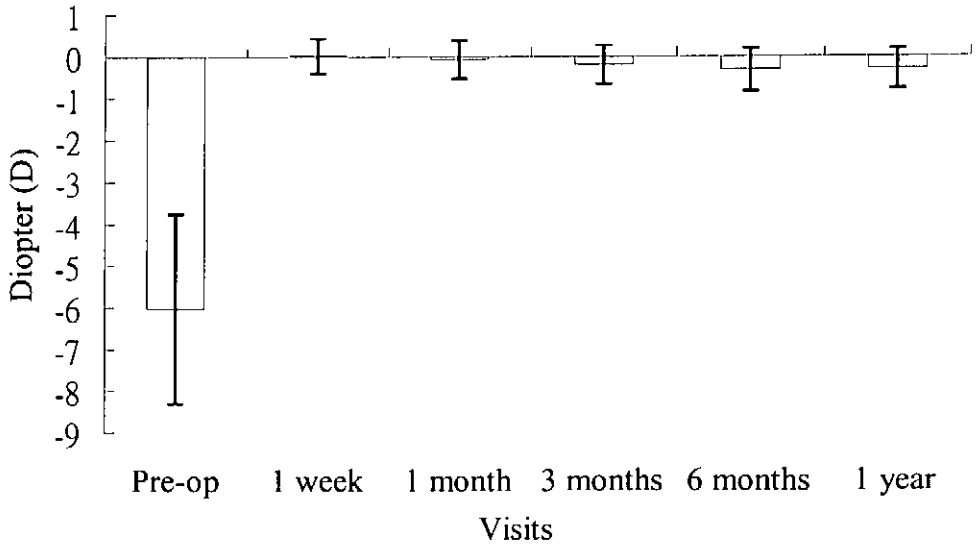
Fig. 3.2b. The differences in log contrast level of individual spatial frequency (n=41). Y-axes are log contrast sensitivities and x-axes are different visits. 1: pre-LASIK; 2: one week; 3: one month; 4: three months; 5: six months and 6: one year after LASIK. The error bars show 1 SD.



3.3.7.2 Relationship between refractive error and change of contrast sensitivity

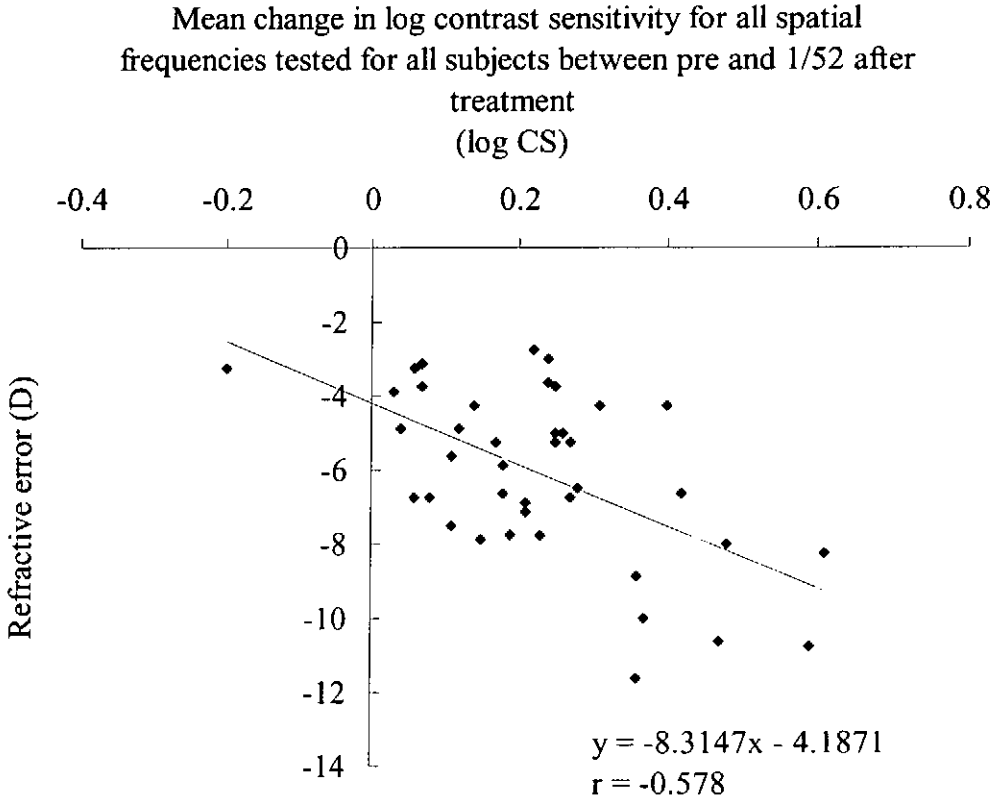
There were statistically significant changes in the mean spherical equivalent refractive error (SERE) in the visits after treatment [RM ANOVA, $F(4, 37) = 5.054$, $p = 0.002$]. SERE values at different visits (excluding the pre-LASIK visit) were compared pair-wise with the SERE one year after treatment. All showed statistically significant differences (post-tests, $p < 0.05$) except the SERE for six months. Fig. 3.3 shows the regression in SERE which occurred with time. (Please refer to Appendix 2 for numerical results.)

Fig. 3.3. The mean spherical equivalent refractive error at different visits (n=41). The error bars show 1 SD.



There was a statistically significant relationship (Peason's correlation, r = –0.578, $p<0.001$) between the mean difference in contrast sensitivity (ΔCS) for all spatial frequencies before and one week after LASIK treatment and refractive error (Rx) before LASIK. Figure 3.4 shows the change in contrast sensitivity plotted against refractive error before LASIK. The regression line and its equation are shown.

Figure 3.4. Relationship between baseline refractive error and mean change in contrast sensitivity for all spatial frequencies tested for all subjects.



3.3.7.3 Mean visual acuity changes after LASIK

There were no statistically significant changes in unaided visual acuities in the visits after LASIK treatment [RM ANOVA, $F(4, 37) = 1.726$, $p=0.147$]. There were statistically significant differences in the aided visual acuity before and after LASIK treatment [RM ANOVA, $F(5, 35) = 3.94$, $p=0.006$]. In post-tests, the mean aided visual acuity before treatment (baseline) was compared with the values found at different post-operative visits (1 week, 1 month, 3 months, 6 months and 1 year). Statistically significant differences were found only for baseline versus one week after treatment ($p=0.001$). Figs. 3.5 and 3.6 are graphical presentations of the mean acuities of the subjects. Please refer to Appendix 1 for numerical results.

Fig. 3.5. Mean unaided visual acuities after LASIK treatment (n=41). The error bars show 1 standard deviation.

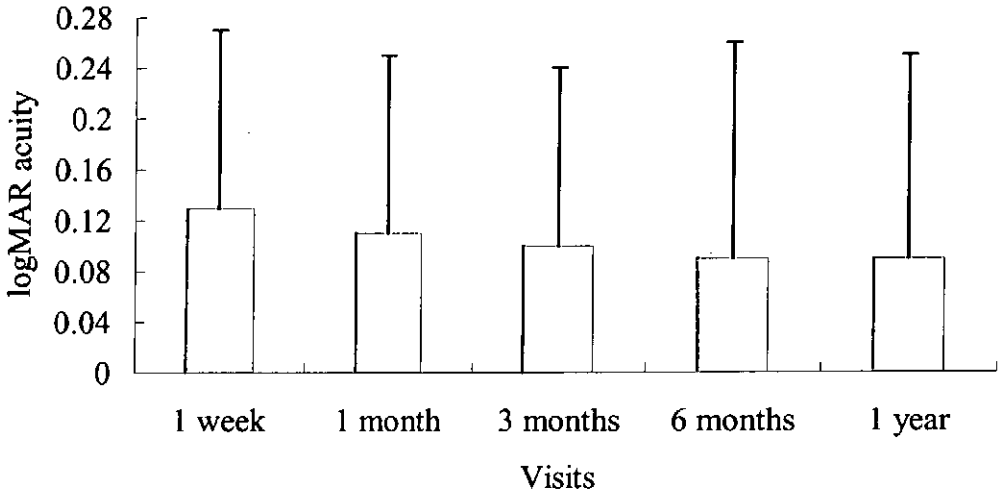
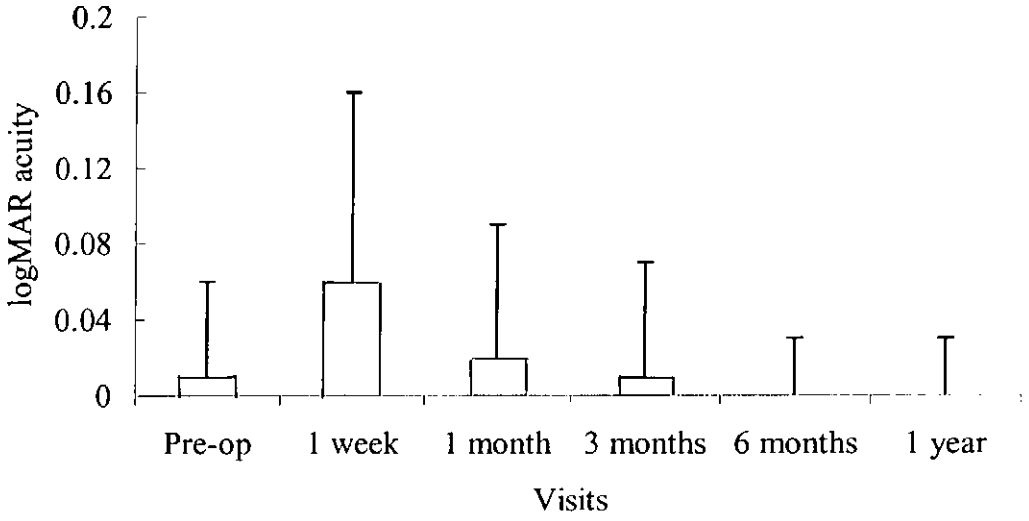


Fig. 3.6. Mean best corrected visual acuities before and after LASIK treatment (n=41). The error bars are 1 standard deviation.



3.3.8 Discussion

Contrast sensitivity, a measure likely to be more sensitive to subtle changes in visual functions than visual acuity tests (Sekuler, 1974; Bodis-Wollner et al., 1980; Sekuler et al., 1982;), was used in this experiment. In the present study, statistically significant decreases were found in contrast sensitivity following LASIK. In contrast, there was only a mean decrease of two letters in logMAR scale of aided visual acuity one week after LASIK. These findings support to the premise that contrast sensitivity is a more sensitive measure then visual acuity. The possible causes of change in contrast sensitivity in the present study will be discussed in this section.

3.3.8.1 Comparison between present study and previous findings

Contrast sensitivity for all tested spatial frequencies decreased in a similar manner after LASIK treatment and had returned to pre-LASIK levels six months after treatment. Pérez-Santonja et al. (1998) and Mutyala et al. (2000) also recently investigated the effects of LASIK on contrast sensitivity, using the CSV 1000E and CSV 1000 (Vector Vision, Dayton) respectively (see Chapter 1, Section 1.13.3). Pérez-Santonja et al. found contrast sensitivity decreased one

month post-operatively for spatial frequencies of 3 and 6 cpd and recovered within three months after treatment. Mutyala et al., on the other hand, found that contrast sensitivity was depressed at 6, 12 and 18 cpd one week after LASIK, but had returned to normal values one month post-operatively.

The results of these studies were different from the present one that, a general depression of contrast sensitivity was found and contrast sensitivity took a longer time, at least six months, to recover fully to the pre-operative level. A possible reason for the differences in recovery time is the difference in contrast sensitivity units used, the step sizes in the two earlier studies being more coarse.

3.3.8.2 A possible learning effect

The present study used a computerized unit to generate the gratings. The sequences of presentation of the seven preset spatial frequencies were fully randomized, eliminating the possibility of memorization. There could, however, have been a learning effect, and a small experiment was conducted to explore this possibility. There was no trend suggestive of a learning effect and the results are shown in Appendix 3.

3.3.8.3 Refractive error and contrast sensitivity

It is commonly assumed that if LASIK does adversely affect contrast sensitivity, the higher the refractive error of the patient before treatment, the more corneal tissue to be ablated, and the greater the adverse effect. The results of the present study indicate that this assumption is correct.

3.3.8.4 Causes of change in contrast sensitivity

A number of studies have shown both optical and neural factors may cause reduction in contrast sensitivity. Campbell and Green (1965), using a double-pass technique, found that neural factors affect the contrast sensitivity in the high spatial frequency region about twice as much as optical factors. Enroth-Cugell et al. (1980) suggested that loss of ganglion cell causes a reduction of contrast sensitivity. They measured the contrast sensitivity of X and Y ganglion cells of cats under different oxygen tensions and found that hypoxia of the retina causes a reduction in contrast sensitivity. Owsley et al. (1983) found that retinal illuminance affects contrast sensitivity, a reduced retinal illuminance causing decrease of contrast sensitivity in the high spatial frequency region. Calver et al. (1999) compared the contrast sensitivity and monochromatic

aberrations in young and older eyes. They found that with natural pupils, the older group showed lower contrast sensitivity and smaller wave-front aberrations compared with the younger group, but for a given pupil diameter, the wave-front aberrations were higher in elderly group. They suggested that the reduction in contrast sensitivity was not due to increase in aberrations. Kline et al. (1983) found that age-related loss of contrast sensitivity in intermediate and high spatial frequencies was mostly due to age-related optical differences. Wright and Drasdo (1985) indicated that such a decrease could be accounted for by reduction of pupil size, causing a reduction in retinal illuminance.

3.3.8.5 Neural change after LASIK

Neural factors as discussed above will affect contrast sensitivity. The question is, will LASIK cause neural change of the eye? Parisi et al. (1999) investigated the correlation between visual function, including contrast sensitivity, and nerve fiber layer thickness in eyes affected by ocular hypertension. They found that the thinner the layer, the worse the visual function. Using the GDx Nerve Fiber Analyzer, Gürses-Özden et al. (2000) and Tsai and Lin (2000) found that the total mean retinal nerve fiber layer and the superior, inferior, temporal, nasal and the

mean retinal nerve fiber layers were thinner after LASIK. Since the nerve fiber thickness as measured by GDx depends on the corneal compensator inherent in the device, they speculated that photorefractive surgery might produce a change in corneal birefringent properties that alter GDx measurement. However, Choplin and Schallhorn (1999) found that in PRK patients, there was no statistically significant change in GDx results, disagreeing with the assumption made by Gürses-Özden et al. The effect of LASIK and other photorefractive surgery on the retinal nerve fiber thickness is presently uncertain. If LASIK does affect the retinal nerve fiber thickness, it might also affect the contrast sensitivity after the treatment. However, since the results of the present study show that the reduction of contrast sensitivity after LASIK treatment is not permanent, it is unlikely to be a neural effect.

3.3.8.6 Optical change after LASIK

LASIK alters the corneal structure, and studies have shown that it induces aberrations of the eye (as mentioned in 1.13.8 and 1.13.9). The results of the present study suggest that that corneal change (an optical factor) is a major reason for decrease of contrast sensitivity after LASIK. In Experiment 6 of the

present study, corneal clarity before and after LASIK is evaluated in order to determine the relationship between contrast sensitivity changes and corneal clarity changes.

3.3.8.7 Change in the corneal structure after LASIK – endothelium

Many studies have investigated the effects of photorefractive surgery, including LASIK, on mammalian corneal endothelia. Pérez-Santonja et al. (1997), Kent et al. (1997), Jones et al. (1998) and others who examined the endothelial cell density, size and cell hexagonality, indicators of endothelial health, found that photorefractive surgery, including LASIK, causes no damage or loss to corneal endothelium. These are not surprising findings as in LASIK, ablation takes place only at the stromal level, and the corneal endothelium is untouched during the procedure. Jones et al., however, suggested that long-term follow-up (five to ten years) was needed to confirm endothelial safety after photorefractive surgery.

3.3.8.8 Changes in corneal structure after LASIK – epithelium and stroma

The integrity of the superficial corneal layer, the epithelium, is maintained in LASIK treatment. Kato et al. (1999) found that the wound healing process after

LASIK was not associated with inflammation and was slow. Amm et al. (1996) suggested that as the superficial corneal layer was maintained intact, it diminished stromal remodeling. Such a minor stromal wound healing response after LASIK might prevent the development of an optical barrier.

There have been reports of inflammation after LASIK treatment. Helena et al. (1997) reported that epithelial cells might enter the lamellar interface during flap opening, causing epithelial in-growth. Interface opacities or inflammation may occur. None of the subjects in the present study developed this complication, and thus changes in epithelium and stroma due to inflammatory processes cannot account for the decrease in contrast sensitivity in the present study. However, this does not mean there was no haze or that there was excellent corneal clarity after LASIK treatment. Experiment 6 in the present study addresses this issue and details are given later. Another optical factor that may affect contrast sensitivity after LASIK is glare and Experiment 4 investigates the effect of glare on contrast sensitivity after LASIK treatment. Please refer to Chapter 4 for details.

3.3.8.9 Change in retinal image size after LASIK

Although the mean contrast sensitivity of the subjects decreased after LASIK, there was one subject (#02) in whom contrast sensitivity improved following surgery. Spectacle magnification changes before and after LASIK may explain this unexpected result. As mentioned in Chapter 1, owing to the change from myopia to emmetropia (or near emmetropia) the size of the retinal image after LASIK is larger than that before. This increased retinal image size may dilute the adverse effect of LASIK on contrast sensitivity. In the subject with improved contrast sensitivity after LASIK, the mean spherical equivalent refractive error was –3.25 D prior to surgery and +0.125 D one week after surgery. Applying the spectacle magnification formula for a thin lens with a known viewing distance (Rabbets, 1998),

$$SM = \frac{A - L}{A - L - F}$$

where A is the dioptric equivalent of the vertex distance, L is the dioptric equivalent of the object distance and F is the back surface power of the spectacle lens. The vertex distance was 14 mm and the object distance was 1 meter, thus the lens magnifications before and one week after surgery were 0.955 and 1.002 times

respectively. When the subject viewed a target of gratings of 20.5 cpd with these spectacle corrections before and after LASIK, the actual spatial resolution of the retinal image sizes would become 21.45 and 20.45 cpd respectively. In a typical contrast sensitivity function curve, the threshold contrast sensitivity value at 20.45 cpd should be higher than a value at 21.45 cpd. The magnification may give a false impression that contrast sensitivity improved following LASIK.

An apparent return of contrast sensitivity to pre-LASIK levels after treatment may not mean a fully recovery has occurred when the magnification effect is taken into account. For example, in subject #01, who had high myopia prior to LASIK, the contrast sensitivities for all spatial frequencies had returned to the pre-LASIK level one year after treatment. The spherical equivalent refractive errors of the subject before and one year after LASIK were –8.25 D and –0.25 D respectively. Using the same mathematical calculations, the spectacle magnifications before and after surgery were 0.895 and 0.996 respectively. Then, a target of 20.5 cpd gratings would become 22.91 and 20.58 cpd. The same measured threshold values for these two different spatial frequencies indicates that the pre-LASIK contrast sensitivity value may have been superior to the value one year after LASIK.

LASIK-induced aberrations and magnification effects may both contribute to the change in contrast sensitivity after LASIK. One will reduce the sensitivity but other will give a false enhanced sensitivity, and the overall result will depend on which is the dominant factor. Although LASIK-induced aberrations seems to be the predominant factor in the present study, as a decrease in contrast sensitivity was demonstrated, the magnification effect should not be over looked especially in cases of untoward results.

3.3.8.10 Additional statistical analysis

Considerable inter-subject variation was be found in the contrast sensitivity values, and directly analysis of the data may mask the effect of LAISK on contrast sensitivity if the variability between subjects is greater than the variability between visits. To try to minimize the effect of between-subject variation, each post-LASIK contrast sensitivity value was divided by the pre-LASIK value, producing ratios (Appendix 7). The pre-LASIK value was expressed as 1. This puts subjects on a common basis and should better reveal the trends across time.

There were statistically significant differences (RM ANOVA, $p<0.05$) between the

baseline ratio (1) and the ratios at different visits for all spatial frequencies except 0.8 and 20.5 cpd (RM ANOVA, $p>0.05$). As in the analysis reported in section 3.3.7, the contrast sensitivity values for those affected spatial frequencies had returned to the pre-LASIK level at the one year post-LASIK visit ($p>0.05$). It is difficult to account for the diverse findings for spatial frequencies 0.8 and 20.5 cpd.

3.3.8.11 General visual assessments

Although the differences in the aided visual acuities before and after LASIK treatment were statistically significant, the changes were clinically small, less than one line logMAR. The slightly improvement of the aided visual acuity at about six months after LASIK to pre-LASIK level should be due to the spectacle magnification as mentioned above. This magnification effect became dominant after the other optical side effect of the treatment subsided.

Post-LASIK, the unaided visual acuities did not vary, supporting the suggestion that visual acuity may not be a good indicator of subtle changes in visual function, at least within the time-frame of the measurements carried out.

Post-LASIK, there was a small regression in mean refractive error, less than 0.5D,

six months to one year after treatment. However, considering the constancy of unaided visual acuity after treatment, this regression in myopia was not clinically significant.

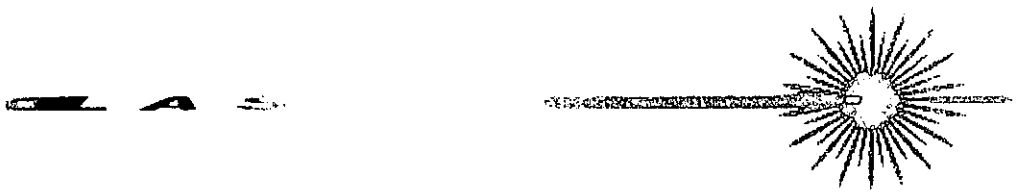
3.3.9 Summary and Conclusions

The present experiment evaluated the effect of LASIK on contrast sensitivity, a measure which provides a wider range of target sizes and luminances, and which is likely to be more sensitive to subtle changes than visual acuity tests. Contrast sensitivity was measured using a computer-based instrument. Measurements were carried out before, and for one year after LASIK. There was a general depression in contrast sensitivity after LASIK treatment. Contrast sensitivity took six months to one year to recover to pre-operative levels.

The non-permanent depression in contrast sensitivity does not seem to be related to neural factors. Tissues repair processes such as inflammation are also unlikely to be the source of reduction in contrast sensitivity and therefore optical factors seem to be the most likely source.

Chapter 4

Glare sensitivity before and after LASIK



4.1 Introduction

A sensation of glare is a common complaint in the days immediately after LASIK surgery, especially at night. In this chapter, the development of a new glare tester which provides quantitative measures of glare sensitivity is described. Its effectiveness was tested prior to use on LASIK subjects. The glare sensitivity values before and after LASIK were then compared, so that the effect of LASIK on glare sensitivity was determined.

4.1.1 Definition of glare

Glare is the sensation produced by luminance within the visual field that is sufficiently greater than the luminance to which the eyes are adapted to cause annoyance, discomfort, or loss in visual performance and visibility (Nadler et al., 1990). Glare resulting in reduced visual performance is called disability glare.

Glare may be caused by phenomena like scattering of stray light from the ocular media or halos produced by aberrations, internal reflection or diffraction of the eye. Fry and Alpern (1953) suggested that the "veiling luminance" produced by stray light within the eye causes an actual and perceptual reduction in retinal image contrast, the more the scattered light, the greater the reduction in contrast.

4.1.2 Changes in retinal image contrast under glare source in the normal cornea

The reduction in contrast which results from a glare source can be described mathematically:

$$\frac{L_b - L_t}{L_b + L_t} \times 100\,(\%)$$

where L_b and L_t are the background and target luminance respectively.

Assuming that the target luminance is X units, then the background luminance is 100-X units. The contrast of the target is

$$\frac{(100 - X) - X}{(100 - X) + X} \times 100(\%) = 100 - 2X(\%)$$

Now, if an extraneous light of, say, 50 units is directed to the target, then the

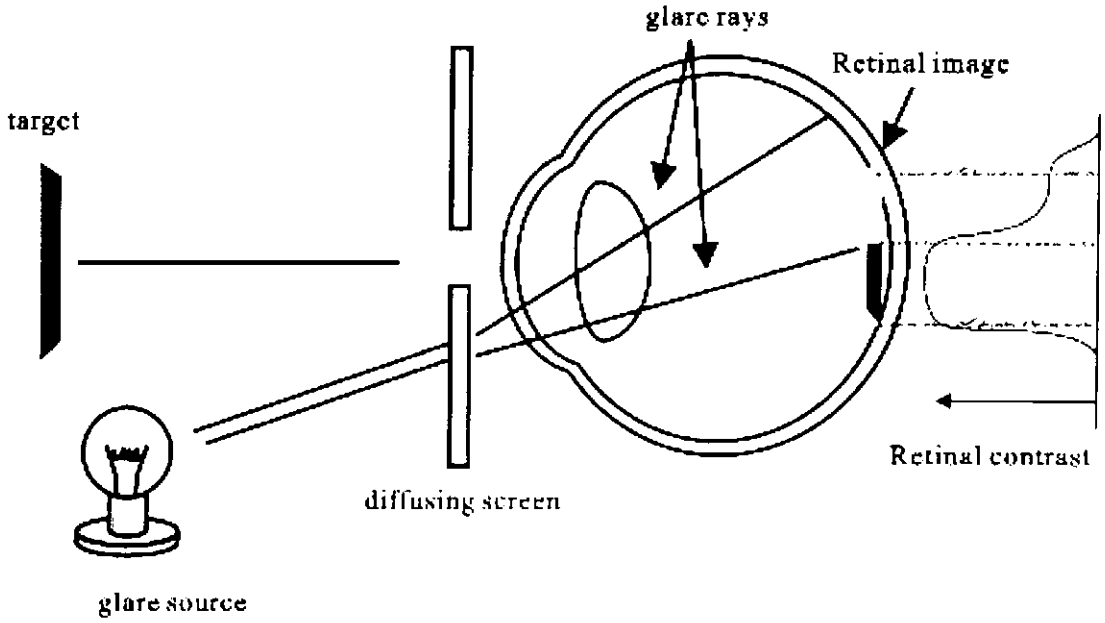
contrast of the target will become

$$\frac{(100-X+50)-(X+50)}{(100-X+50)+(X+50)}\times 100 = 50-X$$

This extraneous light halves the contrast of the target.

A diagram representation of the contrast profile of the retinal image with and without glare is shown in Fig. 4.1

Fig. 4.1. Contrast profile of the retinal image with and without glare.



4.1.3 Glare tester

It is a relatively straightforward task to quantify the amount of light scattered by various ocular tissues by means of photoelectric devices, however, patients' subjective visual experiences should also be investigated. LeClaire et al. (1982) found that their patients with cataract still had good visual acuity but poor contrast sensitivity when a glare source was present. This indicates that visual acuity testing alone is not sensitive enough to identify or quantify a glare effect.

Many researchers have attempted to investigate light scattering and glare using different methods, such as the Miller-Nadler glare tester, the Vistech MCT8000, the van den Berg Straylightmeter, and the Brightness Acuity Tester (Miller et al., 1972, Paulsson and Sjöstrand, 1980; LeClaire et al., 1982). These glare testers use clinical available visual testing charts with external glare source. The chart may comprise in letters or sine-wave gratings. The glare sources can be a multiple point source or a diffused one and surround the target. The glare source dilutes the contrast and the luminance of the retinal image. Thus the retinal image will be different from ambient condition. Score is marked according to how well the subject can see the chart. Elliott and Bullimore (1993) conducted a study to assess the reliability, discriminative ability and validity of the above glare tests. They

found that the Miller-Nadler glare tester was poor at detecting subtle changes in the ocular media because of its large step sizes at low contrast thresholds. The Vistech MCT8000 also showed poor reliability, limiting its usefulness. Miller et al. (1972) suggested that a glare tester should include a large circular fluorescent dazzle glare source, and the targets should be black in color on a light background. The background luminance can be altered by adding neutral density filters.

4.1.4 Light scattering in corneal lesions

Corneal lesions, for example, scar, haze and edema, increase light scattering and degrade the contrast of the retinal image. Miller and Miller (1981) simulated keratotomized corneas using clear acetate sheets with patterns of radial keratotomies etched on the surface. They confirmed that the thicker the scar and the closer it was to the center of the cornea, the worse should be the contrast sensitivity and glare disability.

4.1.5 Light scattering and corneal haze

As mentioned above, a corneal lesion will affect the retinal image contrast by increasing the amount of light scatter or by reducing the light transmission to the retina. In LASIK, a corneal flap is opened and stromal tissue removed, and this

will certainly affect light rays passing through. A number of studies have compared the light scattering after LASIK and PRK. Jain et al. (1995) used rabbit eyes to demonstrate that corneal light scattering was significantly lower after LASIK than after PRK. Chang et al. (1998) also used rabbit eyes to compare the corneal light scattering with LASIK and PRK, and their findings were similar to those of Jain et al.. Wachtlin et al. (1999) compared the immunohistology of corneal wound healing after PRK and LASIK, and found that LASIK caused less stromal reaction than PRK. Kato et al. (1999) found that the inflammatory and wound healing reactions were weak after LASIK, and that there was no subepithelial haze because epithelial cells and keratocytes were not activated.

4.1.6 Refractive surgery and glare

Krueger and Seiler (1997) found that distortion of vision, in the form of glare and halos, was one of the major concerns following PRK. Tengroth et al. (1993), Seiler and Wollensak (1993) and Dello Russo (1993) reported that the sensation of night glare in their subjects increased after PRK. As mentioned in Chapter 1, there have not been many quantitative studies of glare sensitivity after LASIK. In the present study, glare sensitivity will be evaluated using a newly designed glare tester.

4.1.7 Aims of study

The aim of this experiment was to determine the effect of LASIK on glare sensation by comparing contrast sensitivity without and with glare, at different time intervals. Also, the time required for recovery of contrast sensitivity under glare will be found.

Measurements were carried out at six different times, pre-operatively and one week, one month, three months, six months and one year post-operatively. In addition, the subject was asked about the sensation of glare after treatment.

It was hypothesized that contrast sensitivity under glare conditions would decrease after LASIK treatment because of increased scattered light from the cornea.

4.2 Development of new glare tester

A new glare tester, based on the criteria suggested by Miller et al., was developed for the present work. A tearscope (Keeler, Germany) was used as the glare source. The tearscope is bowl-shaped (60 mm diameter) and a round fluorescent tube is fixed between the bowl and a translucent plastic insert. In the middle of the bowl, there is a round aperture (25 mm diameter) through which the subject looks at the

test target. Fig. 4.2 illustrates the set up.

Fig. 4.2a. The tearscope used.

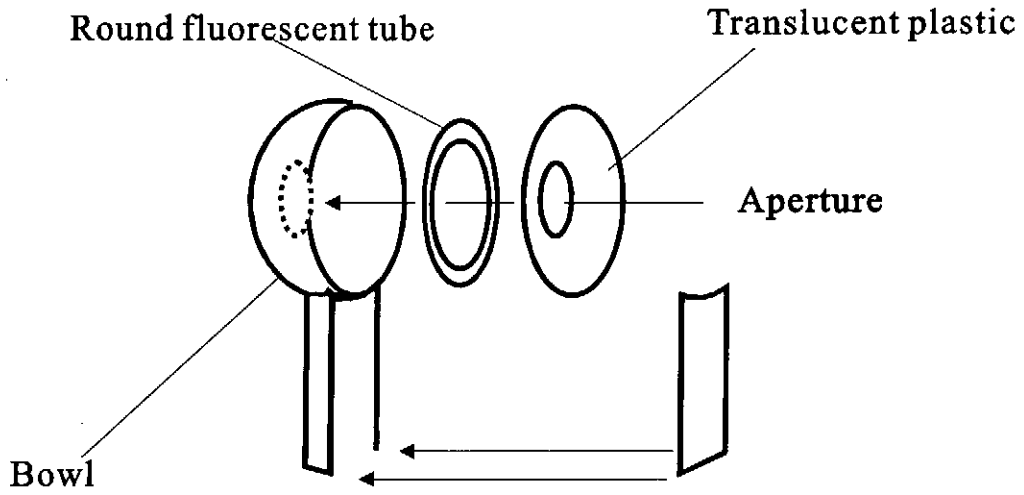
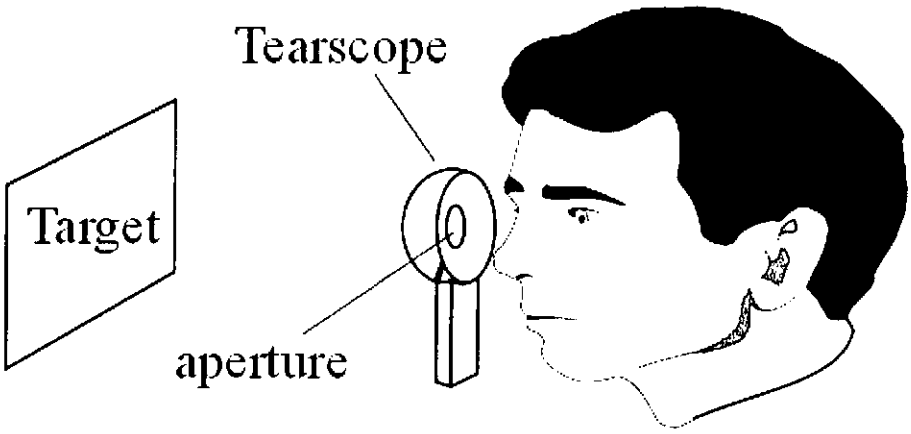


Fig. 4.2b. The tearscope is placed in front of the eye under examination and the subject views the target through the aperture.



The luminance of the tearscope was set to level-4 (maximum luminance of the device, 270 cd/m^2). The tearscope was placed in front of the eye (the translucent plastic in contact with the frontal orbit) and the subject looked at the test target through the aperture. The tearscope then provided a large circular glare source relative to the size of the test target. The effect of glare on contrast sensitivity was quantified by measuring contrast sensitivity without and then with the glare source. Contrast sensitivity was measured using the standardized protocol described in Chapter 3.

4.3 Experiment 3

To determine the effectiveness of the newly designed glare tester

4.3.1 Objective

The objective was to evaluate the effectiveness of the newly designed glare tester.

4.3.2 Subjects

Eight research students and research staff of the Department of Optometry and Radiography in The Hong Kong Polytechnic University, mean ages 26.4 (SD 2.3) years, participated in this experiment. No ocular disease was detected in any subject, and all had had clear ocular media.

4.3.3 Methods

4.3.3.1 Equipment

Tearscope (Keeler, Germany)

CSF test instrumentation as used in Experiment 2 (Chapter 3).

4.3.3.2 Procedures

1. Subject was informed about the study verbally and via an information sheet (Appendix 5) and was given the opportunity to ask questions.
2. A consent (Appendix 6) form was signed before performing the tests.
3. The subject, wearing clean spectacles for the best visual acuity, sat one meter in front of the VDU.
4. The CSF test was carried out on the right eye only, the left eye being occluded, as described previously.
5. One minute break was then provided.
6. The subject was then asked to hold the tearscope, set to maximum intensity, in front of the eye so that the translucent plastic was in contact with the frontal orbit.
7. The contrast sensitivity test was repeated with this glare source in place.
8. As the subject was unable to see the response box clearly, he or she was asked to say "Yes" if the grating was seen or "No" if it was not seen. Then the examiner would press button A or C as applicable.

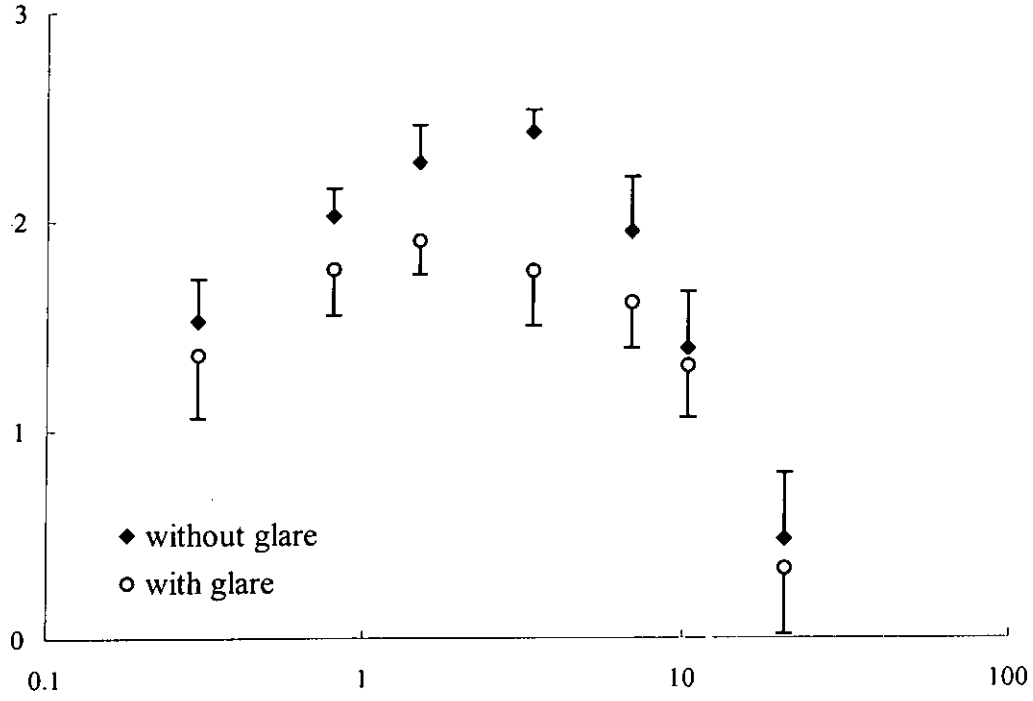
4.3.3.3 Statistical test

RM ANOVA in SPSS was used to compare the results of contrast sensitivity with and without glare.

4.3.4 Results

The mean contrast sensitivities with and without glare of different spatial frequencies are summarized in Fig. 4.3. The numerical data are given in Appendix 4. There was a statistically significant decrease in contrast sensitivity with the glare source in place [RM ANOVA, $F(1, 7) = 93.341$, $p < 0.001$]. There was also a statistically significant interaction between the glare effect and the spatial frequencies [RM ANOVA, $F(6, 2) = 63.526$, $p = 0.016$], that is, some spatial frequencies were affected more than others.

Fig. 4.3. Mean contrast sensitivity for all subjects with and without glare source for each spatial frequency tested.



4.3.5 Discussion

The glare tester clearly showed an effect of glare on contrast sensitivity. The cause of the decrease in contrast sensitivity in most of the spatial frequencies was most likely the increased amount of stray light entering the eye when the glare source was presented. Some of these off visual axis light rays would fall onto the central foveal image, thus decreasing the contrast of the retinal image (Miller et al., 1972). As a result, the contrast threshold was reduced. Fig. 4.2 shows that the decreases in

contrast sensitivity were the greatest in intermediate spatial frequency region. The threshold levels of intermediate spatial frequencies are in the low contrast region (the crest of the contrast sensitivity function curve) compared with other spatial frequencies. The grating in this region can be classified as a low contrast target. A low contrast target is more sensitive to subtle change in background and target luminance (Miller et al., 1972; Hess and Woo, 1978; LeClaire et al., 1982). In contrast, a high contrast target, such as high spatial frequencies gratings, is a non-sensitive indicator of visual performance in patients with media disturbances (Sekuler et al., 1982). It is not surprising, therefore, that for the same amount of glare, the effect on contrast sensitivity for spatial frequencies 3 to 5 cpd was greater than for higher spatial frequencies region.

Steen et al. (1993) derived the following equation to calculate the amount of disability glare (DG) produce by a glare source:

$$DG = \log(1 + \frac{Lv}{Ls})$$

where Lv is the veiling luminance due to a glare source and Ls is the mean luminance of the stimulus. From the equation, if there is no glare source present,

$Lv = 0$, DG will be equal to zero. Using filters and solutions of different concentration of microsphere particles in determining the disability glare, Steen et al. found that either in the present of filters or without filters, there was a linear relationship between the disability glare detected and the concentration of microsphere particles in the solutions (number of scatter). They concluded that disability glare was not affected by the present of a filter since the filter reduced not only the amount of veiling luminance from the glare source, but also the luminance of the target. Their results showed that in the presence of glare the retinal image is the sum of the image without glare plus a uniform background produced by the glare source.

From the disability glare equation above, the amount of disability glare produced in the present study by the tearscope was about 0.57 log units when the tearscope intensity was 270 cd/m^2 (maximum level) and the mean luminance of the target screen was 100 cd/m^2.

4.3.6 Conclusion and summary

The glare tester was able to demonstrate an effect of glare on contrast sensitivity. The effect was apparent from low to intermediate spatial frequency regions. This tester will be used in Experiment 4 to evaluate the effect of LASIK on glare sensitivity.

4.4 Experiment 4

The effect of LASIK on glare sensitivity

4.4.1 Objective

The objective here is to evaluate the effect of LASIK on glare sensitivity using a quantitative method. The glare tester described above was used, and a subjective response to the glare was also requested.

4.4.2 Subjects

Twenty-three subjects, nine male and fourteen female, participated in this experiment. They met the patient selection criteria of the Hong Kong Laser Eye Center given in Chapter 2. The mean age of the subjects was 31.7 (SD 4.94) years. The mean spherical equivalent refractive error before surgery was –6.21 (SD 2.51) D.

4.4.3 Methods

4.4.3.1 Equipment

As described in Experiment 2

4.4.3.2 Subjective response

Subjects were asked to grade the effect of glare in their daily lives. The scale used was from 1, not at all, to 5, severe. The question was answered before the objective glare sensitivity testing procedure was carried out.

4.4.3.3 Procedures

1. Subject was informed about the study verbally and via an information sheet (Appendix 5) and was given the opportunity to ask questions.
2. A consent (Appendix 6) form was signed before performing the tests.
3. The subject, wearing his or her best visual correction, sat 1 m in front of the VDU.
4. The CSF test (used in the Experiment 2) was carried out on the right eye, except that in the case of a subject undergoing LASIK only on the left eye, the test was carried out on the left eye. The other eye was occluded.
5. The standardized procedures were as in Experiment 2.
6. A minute break was then provided
7. The tearscope was adjusted to maximum intensity (level 4).
8. The subject was asked to hold the tearscope in front of the eye under test.
9. With the tearscope on, the contrast sensitivity test was repeated. The starting

level of the CSF test with glare was the threshold level of the subject detected before. The CSF test with glare had ten sequences.

10. Subject was asked to say "Yes" if he or she could see the grating or say "No" if he or she could not see it. Then the examiner would press button A or press button C respectively.
11. A short break was provided if requested.
12. Measurement was carried out immediately prior to surgery, and one week, one month, three months and six months and one year after LASIK treatment.

4.4.3.4 Statistical test

The statistical tests described in Experiment 2 were used in this experiment. The difference in contrast sensitivity without and with glare were compared pre-operatively and at different times post-operatively.

4.4.4 Results

4.4.4.1 Quantitative results

The mean differences in contrast sensitivity, without and with glare for individual spatial frequencies, are summarized in Fig. 4.4. There was no statistically significant difference, in reduction in contrast sensitivity without and with glare, at

different times [RM ANOVA, F (5, 18) =1.253, p=0.326]. The numerical data are given in Appendix 4.

4.4.4.2 Subjective results

The subjective responses to the glare sensation are summarized in Fig 4.5. Considerable glare was experienced immediately post-operatively, however this had decreased just one day post-surgery.

4.4.5 Discussion

4.4.5.1 Additional statistical analysis

There was no statistically significant difference in the reduction in contrast sensitivity without and with glare between visits. An additional statistical analysis was applied in order to reduce the effect of between-subject variation, in which each post-LASIK reduction was divided by the pre-LASIK to obtain a ratio (Appendix 7). The pre-LASIK reduction was expressed as 1. RM ANOVA was used to compare the ratios at different times as in section 3.3.8.10.

There were 5 subjects in whom the contrast sensitivity was the same with and without glare for the spatial frequency 20.5 cpd. The reduction was therefore zero

and so a ratio could not be computed as this would have involved dividing by zero. These cases were excluded in the statistical analysis for this spatial frequency.

The statistical results were the same as in section 4.4.4.1. There was no statistically significant difference in reduction in contrast sensitivity without and with glare, at different times [RM ANOVA, $F(5, 13) = 0.597$, $p > 0.05$].

There are two possible causes for this negative finding. One is related to pupil size and the diameter of the optical ablation zone, the other is the rate of recovery.

4.4.5.2 Pupil size and diameter of the treatment zone

Glare sensation would become worse in dim light, if, when the pupil dilated peripheral light rays were able to enter the eye through the untreated zone of the cornea. The major contributor to glare is the spherical aberration. The refractive surgery procedures increase the asphericity of the cornea causing optical distortions (Seiler et al., 1993; Seiler et al., 1993). El Danasoury (1998) compared night glare after LASIK in eyes with a single ablation zone and in the contralateral

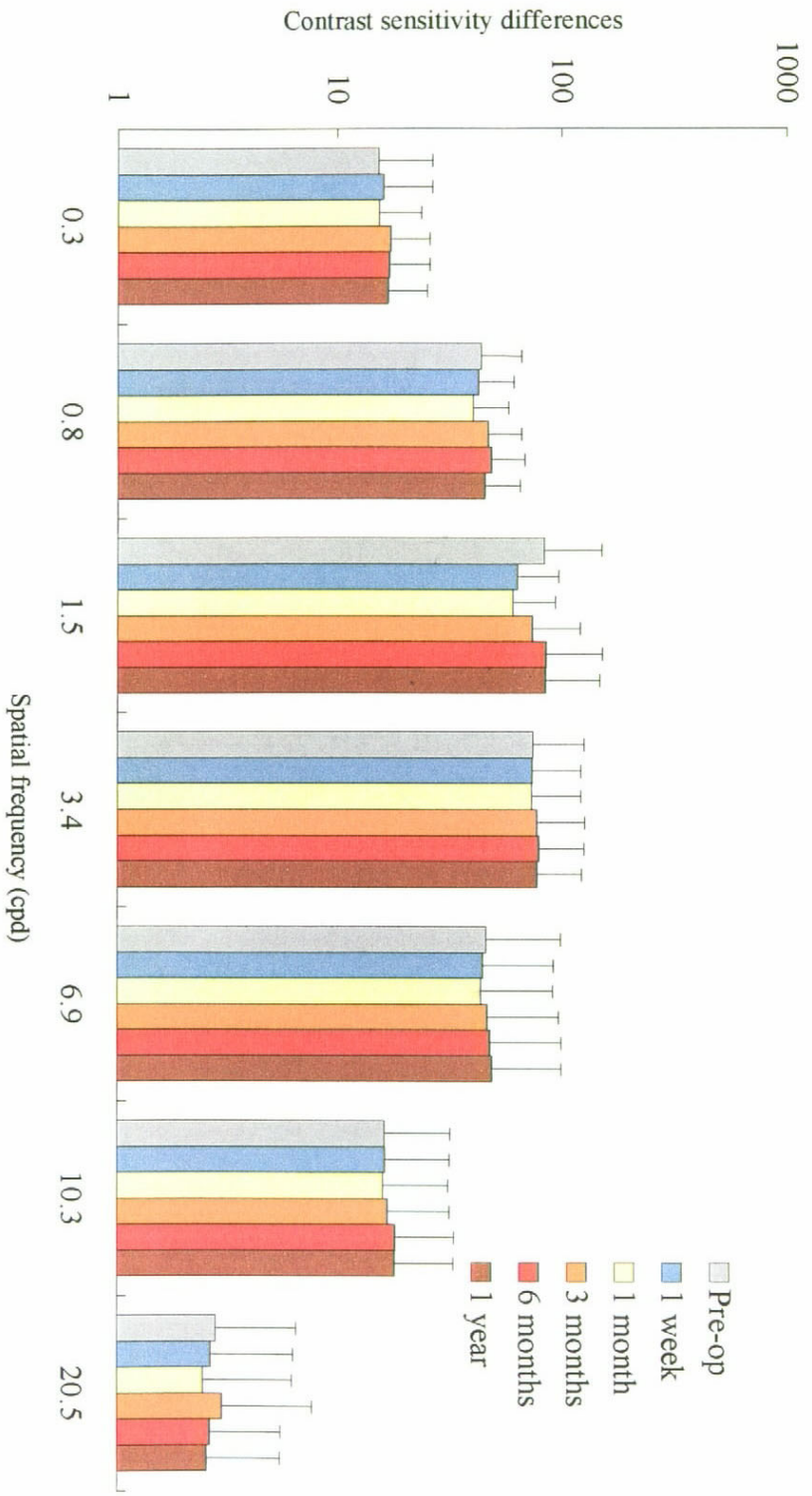
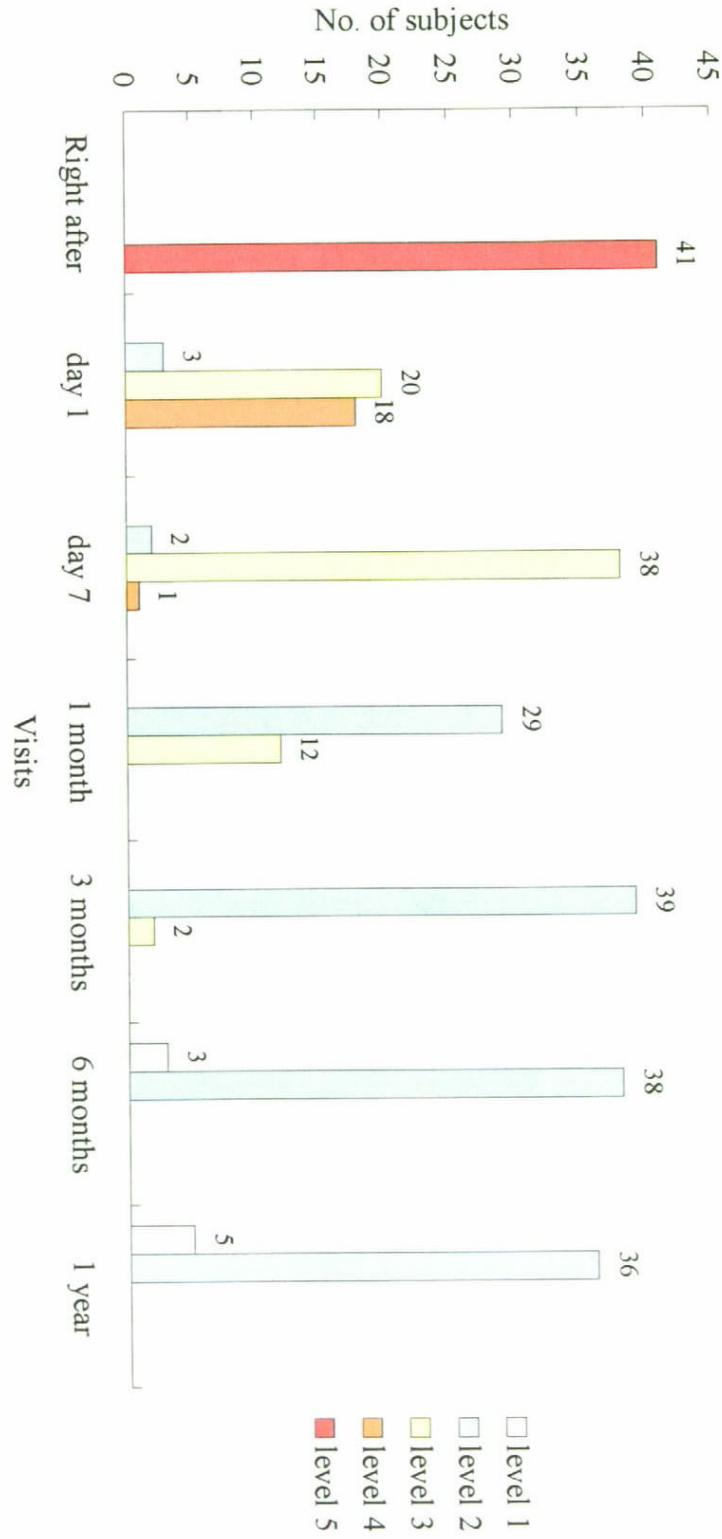


Fig. 4.4. Differences in contrast sensitivities with and without glare at each visit. The error bars show +1 SD.

Fig. 4.5. Subjective glare grading in visits (n=41)



eyes with an ablation zone surrounded by a transitional area (n = 60), and suggested that the larger the treatment area and the more gradual the transition at the edge of ablation, the less the glare produced. In the present study, the mean pupil size under scotopic conditions, measured at the pre-operative visit using a PD ruler, was 5.54 (SD 0.74) mm and the mean optical zone diameter was 5.93 (SD 0.36) mm. Since the mean treatment zone diameter was larger than the mean pupil size even in scotopic condition, the peripheral area of the treatment zone, which has more spherical aberration than the central area, was not used. In addition, the glare source produced miosis, further reducing the diffracted light rays which could pass through the peripheral region of the treatment zone. As a result, no extra glare was produced, compared with the pre-operative level.

4.4.5.3 Modification to the test

A strong glare source, such as the tearscope used in the present study, may cause pupil constriction, however in real life stray peripheral rays at night may not constrict the pupil and may enter the eye. A possible modification to this glare test is to apply a mydriatic agent so that the glare source will not cause miosis. It is possible that this procedure will result in more glare after LASIK.

4.4.5.4 Short-term haze formation

Previous findings show that the cornea after LASIK is stable and that LASIK causes less light scattering than PRK, resulting in less averse effect on vision. However, short-term (within a month) changes in corneal clarity were recorded after LASIK in the present study and details will be given in the next chapter. These short-term and subtle changes might not be sufficient to affect the contrast sensitivity under glare conditions, so that the contrast sensitivity values with and without glare between visits were not significantly different. The results of this experiment were similar to the results of the study conducted by Hersh et al. (2000) who also found no statistically significant difference in mean glare index before and after LASIK.

4.4.5.5 Subjective glare report

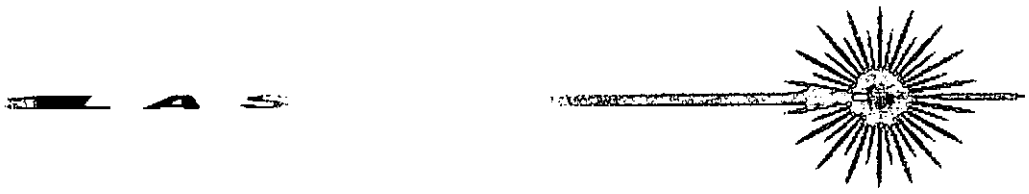
Quantitative tests give important information, however, subjective qualitative feeling should not be overlooked. Although severe glare was reported immediately after treatment (possible due to pain or tearing right after surgery), it subsided quickly, and all subjects felt that they could adapt to the small amount of glare they experienced.

4.4.6 Summary and conclusion

The present experiment evaluated the effect of LASIK on glare sensitivity before and after treatment using both quantitative and qualitative methods. Measurements were carried out before at specific intervals over a 12-month period after LASIK treatment. There was no statistically significant additional glare detected after LASIK treatment. It is possible that pupil miosis under glare conditions reduced the diffraction and scattering of light from the peripheral area of the treatment zone. Subjects reported that the subjective glare sensation subsides very quickly after treatment. In conclusion, LASIK has little or no effect on glare sensitivity.

Chapter 5

Corneal clarity before and after LASIK



5.1 Introduction

The main reasons for the transparency of the cornea are the very small size of the collagen fibrils (240-350 Å) and the close similarity between the refractive indices of the fibrils and the ground substance of the cornea. Any structural changes in the cornea, for example, corneal edema, wound or corneal scar formation, will produce a decrease in the corneal clarity by increasing light scattering.

A number of studies have examined corneal clarity after photorefractive surgery (Chapter 1). Although these studies showed that LASIK causes less corneal light scatter than other photorefractive procedures, for example PRK, nevertheless some corneal light scatter still occurs after LASIK treatment. Clinical tests of corneal clarity, such as the subjective method suggested by Korb and Exford (1968), which

grades central corneal clouding from grade 1 (bare visible) to grade 4 (severe), are too subjective and an objective test is needed.

The development of an objective, sensitive and reliable method to measure corneal clarity will be discussed in this chapter. The method developed was used in determining corneal clarity before and after LASIK treatment.

5.2 Development of corneal section imaging method

5.2.1 The concept of measuring the scattered light from the cornea

The cornea is a highly transparent structure, having about 90% transparency (Feuk and McQueen, 1971). If the cornea appears to be cloudy, it means more light is being scattered from it. If a device can collect and quantify that scattered light then it can provide an objective measure of corneal clarity. In developing such a device, the main difficulty is how to pick up the scattered light, as it is difficult to collect and record the scattered light rays. This is because the amount of scattered light from the cornea is very small and is easily masked by background light.

A number of techniques have been used to measure corneal clarity. The confocal microscope can provide measures of corneal clarity, however its considerable

expense limits clinical use of this instrument (Jester et al., 2001). Scatterometry makes use of a fiberoptic detector to measure back-scattered light from the cornea and can also provide an objective measure of corneal clarity (Jain et al., 1995; Braunstein et al., 1996). Although this technique has been shown to provide reproducible results (Jain et al., 1995; Braunstein et al., 1996), it is still a new device and is not intensively used. Harrison et al. (1995) used a stray light meter to measure forward light scatter from the cornea. They found no difference in measures before and one month after PRK, and so it is possible that a stray light meter is not sufficiently sensitive. In contrast, Lohmann et al. (1992) developed a digital video system to objectively measure scattered light from the cornea. They used a closed circuit digital (CCD)-camera mounted on a bracket on a slit-lamp microscope. A switchable linear polarizing filter, A, was mounted in the light-path between the light bulb and the cornea, distal to the mirror. The filter was divided into two portions, upper and lower, such that their planes of polarization were at right angles to each other. Another fixed polarizing filter, B, was installed inside the CCD-camera between the lens and the detector with a plane of polarization identical to that in the upper portion of filter A in the light-path. When the user switches filter A, it changes from its upper to lower portion such that the planes of

polarization of A and B will be at right angles to each other. The camera was connected to a computer which recorded the images at 256×256 pixel resolution and on a 8-bit gray-scale. The images were then analyzed using commercially available software. Using this device, Lohmann et al. found that corneal light scattering increased after PRK (Lohmann et al., 1992). The above technique was made more "user-friendly" and used in the present study.

5.2.2 Computer imaging

Analyzing the slit-lamp image can provide objective information about the amount of light scattered from cornea. The computer image of the corneal section can be mono color or color. A black and white picture is composed of only two colors of pixel and the quality of the picture is poor since information is lost because of lack of contrast. A gray-scale picture is also composed of black and white pixels but of 256 different intensities from 0 (black) to 255 (white), and of better quality. The quality of a colored picture depends on the bit value. A digital colored picture can be in 8-bit, 24-bit, Red Green Blue (RGB), 32-bit, Cyan, Magenta, Yellow, Black (CMYK) or higher. The higher the bit value, the more fine the color and the better the quality of the picture.

It is a straightforward task to analyze the pixel intensity by means of commercially available computer software. The user simply moves the cursor to the particular pixel or selects an area to be analyzed, clicks the mouse button and a color index will be provided. In a gray-scale picture, the intensity value will be a single number from 0 to 255. In a color picture, the color intensity index will comprise three numbers in RGB and four numbers in CMYK format, also ranging from 0 to 225.

5.2.3 Corneal clarity index calculation

Figure 5.1 shows how a corneal clarity index can be derived. A 24-bit colored picture is first converted to an 8-bit gray-scale image. The image is composed of pixels which are visible when the image is sufficiently magnified, as shown in Fig 5.1a. The desired area of the corneal section is isolated in one of two ways: either by picking up one pixel and then the computer will select all pixels which have the same color, or by dragging the mouse cursor to select the desired area. By averaging the gray-scale index of the pixels in each row from A to B of the isolated area, a mean gray scale index can be found for each row. Then, the mean gray scale of the rows from A to B can be plotted, giving a gray-scale (corneal clarity) index curve as shown in Fig. 5.1b.

Fig. 5.1a. 8-bit gray-scale picture of a cornea.

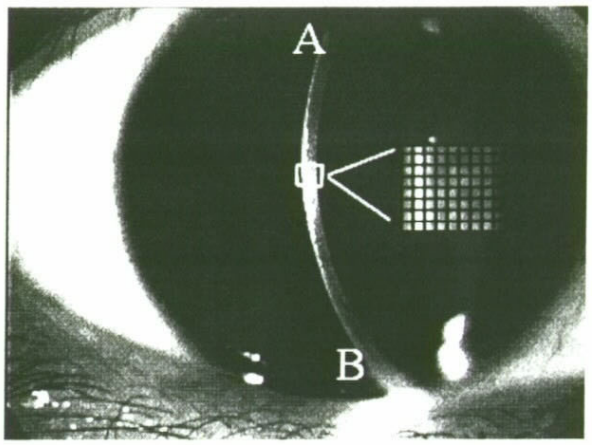
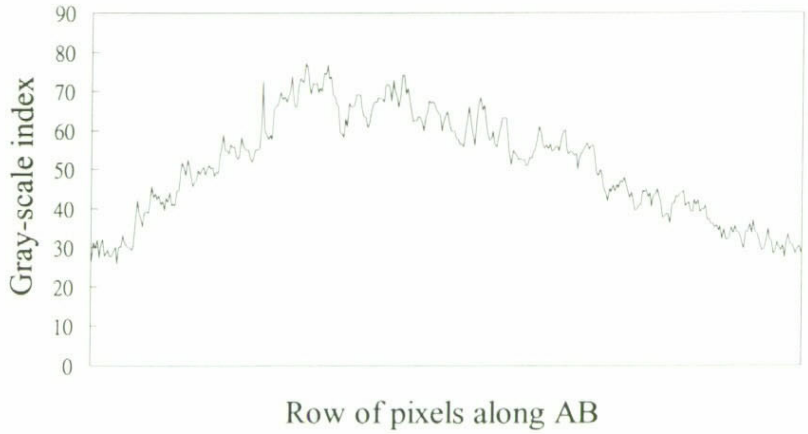


Fig. 5.1b. The gray-scale index of the cornea in Fig.5.1a.



A single index can be specified in terms of the mean of the all indices of all the rows. The less clear the cornea the more the light scattered, so that the corneal section will be more white in color, resulting in a higher the gray-scale index. Thus, the higher the gray-scale index, the lower the corneal clarity.

5.2.4 Fixed-mask modification

One of the steps described above causes variation in the corneal clarity index results, namely, isolating a fixed-size of the image of the corneal section. The computer software can select the pixels of a similar color and group them together, however variation still occurs due to the sine wave edge of the optic section, resulting in poor reliability. If the desired area is isolated manually, the test is no longer objective. Modification was made to the procedure in order to overcome this problem. A fixed area (mask) was preset, then isolation of the desired area was done according to the mask. Therefore, each isolated area had the same number of pixels. With control of the magnification of the bio-microscope and the incident angle of the slit-lamp, the size of the corneal section captured was fixed, resulting in a more objective and accurate corneal clarity index.

5.2.5 Calibration of the method

A method was designed to calibrate the corneal section imaging method. Solutions of milk and distilled water were prepared to simulate a cloudy cornea. A spectrophotometer was used to test the light absorbance of five different samples of solution, 0 (solution A), 0.25, 0.5, 0.75 and 1.0% of milk. The solutions were poured into separate transparent plastics sample cups, and all the cups were then put inside the spectrophotometer. The light source used was visible light of wavelength 550 nm. The results produced were an absorbance index, abs, from 0, no absorption, to 3, 100% absorption. The corneal section imaging method was then carried out. Photographs of the sample cups containing the solutions were taken (The procedures will be described later in Section 5.4.3.2). The abs was determined and then converted to percentage absorbance, and finally the light transmission percentage was derived.

$$\text{Absorbance } \% = \frac{abs}{3} \times 100\%$$

$$\text{Transmission } \% = 1 - \text{Absorbance } \%$$

The differences in clarity indexes between solution A (baseline value) and each of

the other solutions were compared with the light transmission percentage so that the relationship between change in corneal clarity index and light transmission percentage could be determined.

5.2.6 Calibration results

The concentration of the milk solutions and the absorbance of the solutions are shown in Table 5.1. The relationship between the absorbance and milk concentration is shown in Fig. 5.2. Fig. 5.3 is the plot of light transmission against change of clarity index.

Fig. 5.2. Absorbance (abs) of the milk solutions.

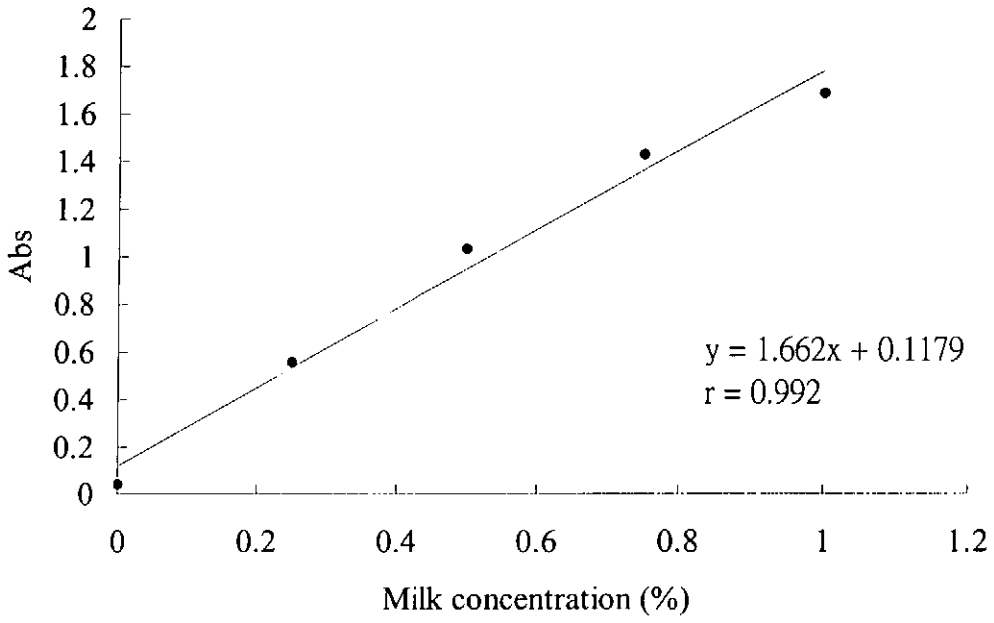
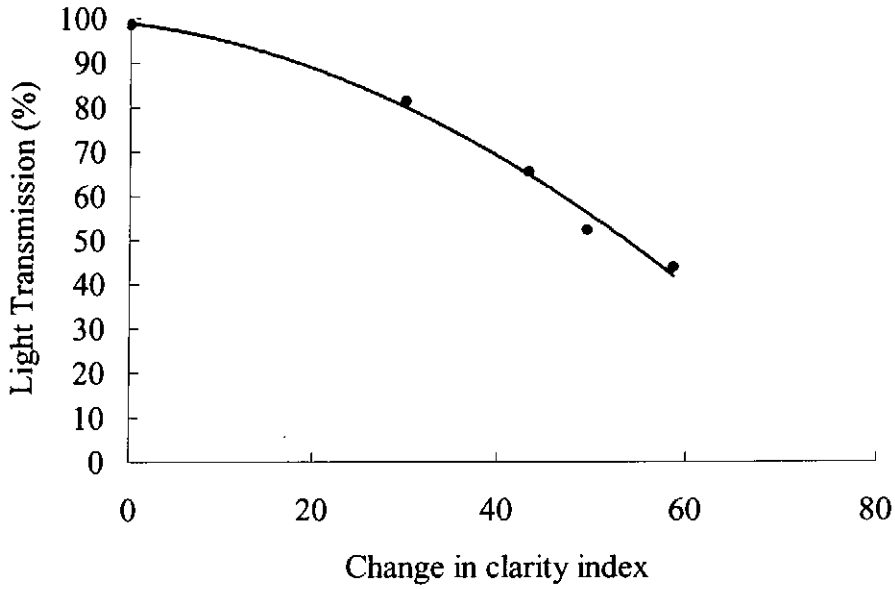


Table 5.1. Concentrations of the milk solutions, the absorbance, transmittance.

Solution	A	B	C	D	E
Milk (ml)	0	0.0025	0.005	0.0075	0.01
Distilled water (ml)	1	0.9975	0.995	0.9925	0.99
Milk conc. (%)	0	0.25	0.5	0.75	1.0
Absorbance	0.042	0.5571	1.0331	1.4281	1.684
Absorbance (%)	1.4	18.57	34.44	47.60	56.13
Transmittance (%)	98.6	81.43	65.56	52.40	43.87
Corneal clarity (CC) index	36.71	66.78	79.93	86.16	95.30
Change in CC index	0	30.07	43.22	49.45	56.13

Fig. 5.3. Relationship between solution clarity and light transmission. This was subsequently used to determine the corneal transmission corresponding to different corneal clarity indices.

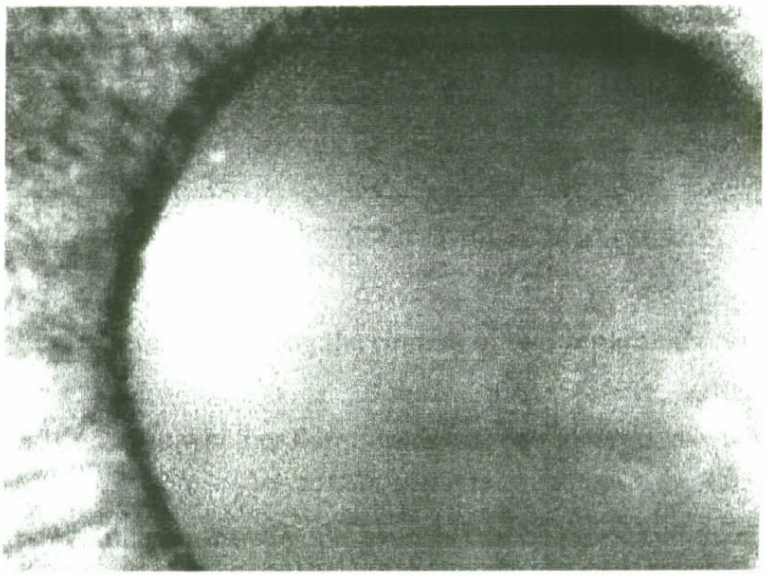


5.3 Purkinje image method

5.3.1 Development of the Purkinje image method

Weale (1992) used Purkinje images to examine the degree of cataract. He utilized a small target comprising a series of black dots attached to a slit-lamp. A sample slit-lamp photograph taken in this study is shown in Fig. 5.4. The gap between each pair of dots doubles progressively, the smallest gap corresponding to optimal retinal resolving power.

Fig. 5.4. Slit-lamp photographs of human crystalline lens using the method described by Weal 1992.

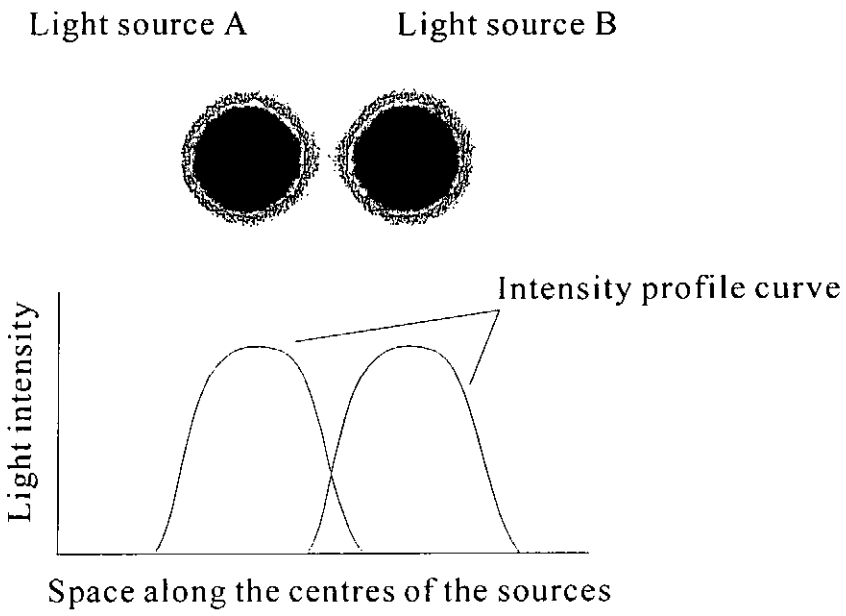


The rationale of the method was that if the examiner could resolve the pattern in the patient's 4th Purkinje images, then the image-forming capacity of the anterior segment must be unimpaired. Computer software can be used to analyze the results. Consider a point source. Its image will also be a point image if the light rays pass though a perfect optical medium. However, aberration and diffraction from the optical media will degrade the quality of the image so that a blur circle will appear around the image. The edge of the image can be considered as a sine wave, the intensity dropping progressively. If the amount of aberration and diffraction increases, the size of the blur circle increases. The blurred areas of the two sources

may overlap each other, and as the overlap increases, at some point the two sources will no longer be seen as separate. Fig. 5.5 is a schematic diagram showing the idea of determining the separation of two point objects by considering their color intensities.

Analyzing the color intensities along the centers of two separated point sources can provide information as to whether the sources can be resolved. According to Rayleigh criterion, images of two point sources can be classified as separate if the color intensity between the centers of the two images drops below 74% of the color intensity of the center of the image (Rabbetts, 1998)

Fig.5.5. The color intensities of two closed point objects.



5.3.2 Image selection

Since the cornea is the main structure in this study, the Purkinje I and II images should be considered. However, the Purkinje I image only gives information about the anterior surface of the cornea, and is not representative of the cornea as a whole. The Purkinje II image should be the most representative because it reflects the state of the whole cornea, however, owing to its low brightness, and the location of the Purkinje II image very close to Purkinje I, it is difficult to observe (Rabbetts, 1998). In the present study, the Purkinje IV image was analyzed with the assumption that LASIK does not affect the crystalline lens structure.

After deciding which image would be examined, the next step is to decide the target to be used. The target should contain two separate sources and their separation should be adjustable. The sources should be bright enough that they can be picked up easily by camera, but should not cause pupil constriction, because a smaller pupil will make the observation of the Purkinje IV image more difficult. Infrared sources seem to be suitable, as infrared is invisible and will not cause pupil constriction. In order to capture the reflected infrared image, infrared-sensitive film is needed. However, this type of film cannot give a real time picture of the image.

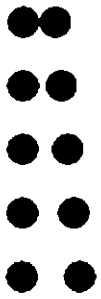
This would have been a problem in the present study, as the subject would have undergone LASIK before the photographs had been developed and printed. It would then be too late to re-take unsuccessful photographs. An infrared sensitive digital video camera overcame this problem, providing a real time picture. The only uncertainty was whether the video camera had high enough resolution and sensitivity to pick up the reflected infrared light. A pilot study was carried out to test the possibility of using an infrared light source and capturing the image using a domestic digital video camera.

Two infrared LED were used as the sources. They were mounted on two movable stands so that the separation between them could be adjusted, and the stands were fixed on a table with a chin rest. The video camera was mounted on the same table. A distance fixation target was used at 4 meters and the subject was requested to settle on the chin rest, looking at the distance target. The two infrared LED were reflected or refracted by the subject's eye and the Purkinje IV image was recorded by the camera. It was found that if the background luminance of the room was high the Purkinje IV image of the infrared LED was difficult to identify. If the room luminance was reduced, large amounts of noise appeared in the picture, this being a

common draw back of domestic video cameras when recording in dim light. The noise degraded the quality of the picture and analysis was impossible. Under these circumstances, it was decided not to use an infrared source.

A target similar to the one used by Weale was then tested. It comprised two rows of black dots, 1 mm in diameter, printed on a transparent sheet. The horizontal separation of the dots increased from 0 mm to 0.8 mm in 0.2 mm steps. Fig. 5.6 shows the target. The target was attached to the reflecting mirror of a slit-lamp which was connected to a digital camera capable of displaying real time photos.

Fig. 5.6. The series of black dots used.



5.4 Experiment 5

Repeatability and sensitivity of two objective corneal clarity tests

5.4.1 Objective

Two objective tests, one utilizing Purkinje images and the other utilizing corneal section imaging, were developed for corneal clarity measurement. The objectives here were to determine the repeatability of the tests and which test was more sensitive to subtle change in cornea clarity.

5.4.2 Subjects

Fifteen volunteers, mean ages 23.27 (SD 2.12) years, participated in this part of the study. Slit-lamp examinations were carried out before the experiment to rule out any corneal abnormalities.

5.4.3 Methods

5.4.3.1 Equipment

- Sony color digital video camera DXC-930P (Sony, Japan) connected to a

slit-lamp.

- Computer graphic software, CorelDraw 9.0.
- Series of black dots printed on a transparency (size and separation as mentioned above) as shown in Fig. 5.6.
- Disposable soft contact lenses (Acuvue, Johnson & Johnson, USA)

5.4.3.2 Setting

For the Purkinje image method, the transparency with the series of black dots (Fig. 5.6) was attached to the reflecting mirror of the slit-lamp. A full aperture with medium intensity beam was used and the angle of incidence of the light beam was 30°. The microscope was normal to the cornea with a 30X magnification and the fixation light mounted on the slit-lamp was used as a fixation target. The Purkinje IV image was captured.

In the corneal section imaging method, the transparency was removed and two crossed Polaroid filters were attached, one to the light source and the other to the objective of the slit lamp. The width of the slit of the slit lamp was 1 mm, with an angle of incidence of 40° and the magnification used was 10X. The fixation light

mounted on the slit-lamp was used as a fixation target and an image of corneal section was captured. The captured pictures from both methods were then converted to 8-bit gray-scale images for analysis.

5.4.3.3 Procedures

1. Subjects were informed about the study verbally and via an information sheet (Appendix 5). Consent forms (Appendix 6) were signed by all participants, who were given the opportunity to ask questions.
2. The Purkinje image method was performed on the right eye of each subject. Three pictures were taken in each measurement and the result was the mean value obtained from the three pictures.
3. The corneal section imaging method was performed on the same eye and again three pictures were taken in each measurement with the result being the mean of the values obtained from the three pictures.
4. Procedures 2 and 3 above were repeated to determine the repeatability of the methods.
5. Keratometry was carried out using a keratometer model OM-4 (Topcon, Japan).
6. Corneal edema was induced in the right eye by having the subject wear a tight

fitting disposable soft contact lens under closed eyelids for 30 minutes.

7. The contact lens was then removed.
8. The Purkinje image method was performed again on the right eye.
9. The corneal section imaging method was then performed.
10. Slit-lamp examination was immediately carried out for the presence of corneal striae, folds or clouding.

5.4.3.4 Statistical analysis

The repeatability value can be found by multiplying the standard deviation of the difference between two successive measurements by 1.96. The sensitivities of the methods were determined by comparing the results before and after corneal edema was induced, using paired t-tests.

5.4.4 Results

In the Purkinje image method, the means of the first and second least resolvable distance of the dots were 0.244 (SD 0.097) mm and 0.249 (SD 0.081) mm respectively. The mean standard deviation of the difference between test and retest results was 0.092 mm. The repeatability value of the test was therefore 0.180 mm

(0.092×1.96).

In the corneal section imaging method, the mean of the first and second corneal clarity indexes were 120.23 (SD 39.79) units and 119.66 (SD 39.86) units respectively. The mean standard deviation of the difference was 2.09 units and the repeatability value of the test was 4.11 units (2.09×1.96).

The least resolvable distance of the dots in the Purkinje image method after corneal edema had induced was 0.017 mm greater than baseline value. That change was not statistically significant (paired t-test, $t = -0.654$, $df = 14$, $p>0.05$).

The mean corneal clarity index in the corneal section imaging method after corneal edema had been induced was 16.24 units greater than baseline value. This change was statistically significant (paired t-test, $t = -5.015$, $df = 14$, $p<0.01$).

No corneal striae, folds or clouding were seen at the end of the experimental procedure.

5.4.5 Discussion

The experimental procedures mentioned above should induce only very small amounts of corneal edema and corneal haze, because there were no corneal folds (>8% swelling), no striae (>4% swelling) and no observable clouding on any of the corneas under test. A very small amount of edema or haze was needed in this sensitivity test because the intention of developing these methods was to identify subtle change in corneal clarity after LASIK treatment.

5.4.5.1 The Purkinje image method

In the Purkinje image method, the least resolvable distance of the dots increased by an average of 0.0266 mm, that is, the change in the least resolvable distance of the dots after corneal edema was induced was smaller than one measurement step (0.2 mm). Considering the repeatability value, 0.135 mm, of this device, 95% of repeated measures were within 0.135 mm of the original measure. In addition, the change in the least resolvable distance of the dot before and after corneal edema induced was not statistically significant. These findings indicate that small amount of change in the least resolvable distance cannot be considered as real change. This method can only provide information regarding a very small area of cornea. If

the haze which occurred was not evenly distributed in the cornea, information might be lost. The Purkinje image method as carried out here was not, therefore a sensitive test for determining subtle change in corneal clarity.

5.4.5.2 The corneal section imaging method

Using the corneal section imaging method, a statistically significant change in corneal clarity was detected. This method was therefore able to detect relatively small amounts of change in corneal clarity.

5.4.6 Conclusion

Corneal section imaging and the Purkinje image method are objective ways to measure corneal clarity. Both are repeatable. The corneal section imaging method was more sensitive than the Purkinje image method in that it could pick up changes in corneal clarity where the Purkinje image method could not. Under these circumstances, the corneal section imaging method was used in determining the effect of LASIK on corneal clarity.

5.5 Experiment 6

The corneal clarity change before and after LASIK treatment

5.5.1 Objective

Reports have shown that the cornea after LASIK is quiet and stable (Jain et al., 1995; Wachtlin et al., 1999). However, the relationship between corneal clarity and LASIK is still not well established. The aim of this study was to measure corneal clarity objectively before and after LASIK treatment, in order to determine to what extent corneal clarity is affected by LASIK and how the cornea recovers in the four-week period immediately following surgery.

5.5.2 Subjects

Twenty-four subjects, ten males and fourteen females, mean age 34 (SD 6.16) years, participated in this study. The selection criteria were the same used in the HKLEC, described in Chapter 2. The mean spherical equivalent refractive error of the eyes under test before LASIK was −5.66 (SD 2.02) D.

5.5.4 Methods

5.5.4.1 Equipment

- Sony color digital video camera CEN50 (Sony, Japan) connected to a slit-lamp microscope. Polaroid filters.
- Computer graphic software, CorelDraw 9.0.

5.5.4.2 Setting of the instrument

The same setting was used as in Experiment 5 (Section 5.4.3.2).

5.5.4.3 Procedures

1. Subject was informed about the study verbally and via an information sheet (Appendix 5) and was given the opportunity to ask questions.
2. These procedures were carried out before, and one, seven and thirty days after LASIK treatment.
3. The subject was asked to look at the near fixation target which was mounted on the slit-lamp. Three corneal section photographs were taken. In cases where the subject would undergo LASIK only on the left eye, photographs of left eye would be taken, otherwise the right eye was photographed.

4. The gray-scale intensity of the photograph corneal section was analyzed utilizing the computer software, CorelDraw 9.0. An index, ranges from 0, black, to 255, white, was obtained by averaging the values from the three photographs.

5.5.4.4 Statistical analysis

RM ANOVA in SPSS was used to analyze the data obtained. The relationship between the corneal clarity index and the spherical equivalent refractive error before LASIK was expressed in terms of Pearson's correlation coefficient.

5.5.5 Results

The mean corneal clarity indices before, one day after, one week after and one month after LASIK treatment of the subjects were 128.76 (SD 4.06) units, 151.07 (SD 40.40) units, 138.20 (SD 40.70) units and 129.50 (SD 42.24) units respectively. The changes in clarity unit were statistically significant (RM ANOVA, $F(3,21) = 21.621$, $p<0.001$). Post-tests showed statistically significant differences when comparing the baseline (pre-operative) index to the indices one day and one week after LASIK, ($p<0.001$), but there was no statistically significant difference when

comparing the baseline index to the index one month after treatment, ($p>0.05$).

When analyzing only the central 3 mm of the corneal section, the clarity indexes became higher (i.e. there was a decrease in corneal clarity). The indexes of pre-LASIK, one day, one week and one month after LASIK were 182.75 (SD 54.48), 211.72 (SD 47.17), 198.57 (SD 51.05), and 186.8 (SD 53.34) respectively, and there was also a statistically significant difference in changes in central corneal clarity indexes (RM ANOVA, $F(3,21) = 26.658$, $p<0.001$). Post-tests also showed statistically significant differences when comparing the baseline (pre-operative) index to the indices one day and one week after LASIK, ($p<0.001$), but there was no statistically significant difference when comparing the baseline index to the index one month after treatment, ($p>0.05$). Corneal clarity, therefore, decreased after LASIK, and return to baseline after the treatment. Fig. 5.7 shows the change in corneal clarity indices with time after LASIK treatment.

There was a statistically significant correlation between refractive error (Appendix 2) and change in corneal clarity index of whole corneal section ($r = -0.56$, $n = 24$, $p<0.005$), however the correlation between change in corneal clarity index and

change in the best-corrected visual acuity (Appendix 1) pre-operatively and one day after LASIK was not statistically significant ($r = 0.069$, $n = 24$, $p>0.05$).

Fig. 5.7. Mean corneal clarity index before and after LASIK treatment (n=24). The error bars show 1 standard deviation.

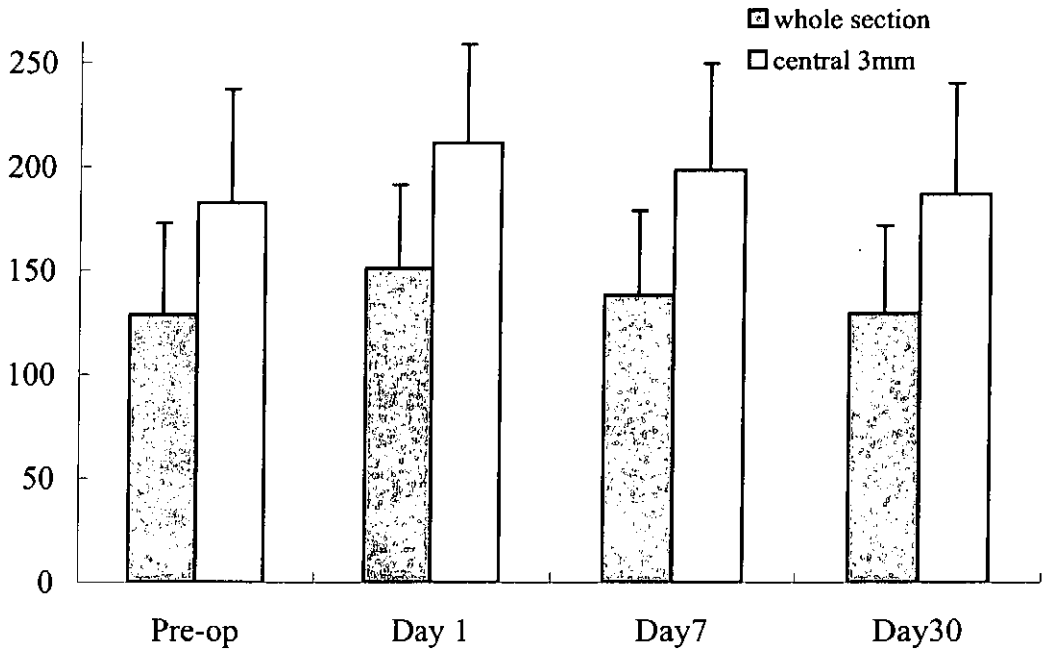
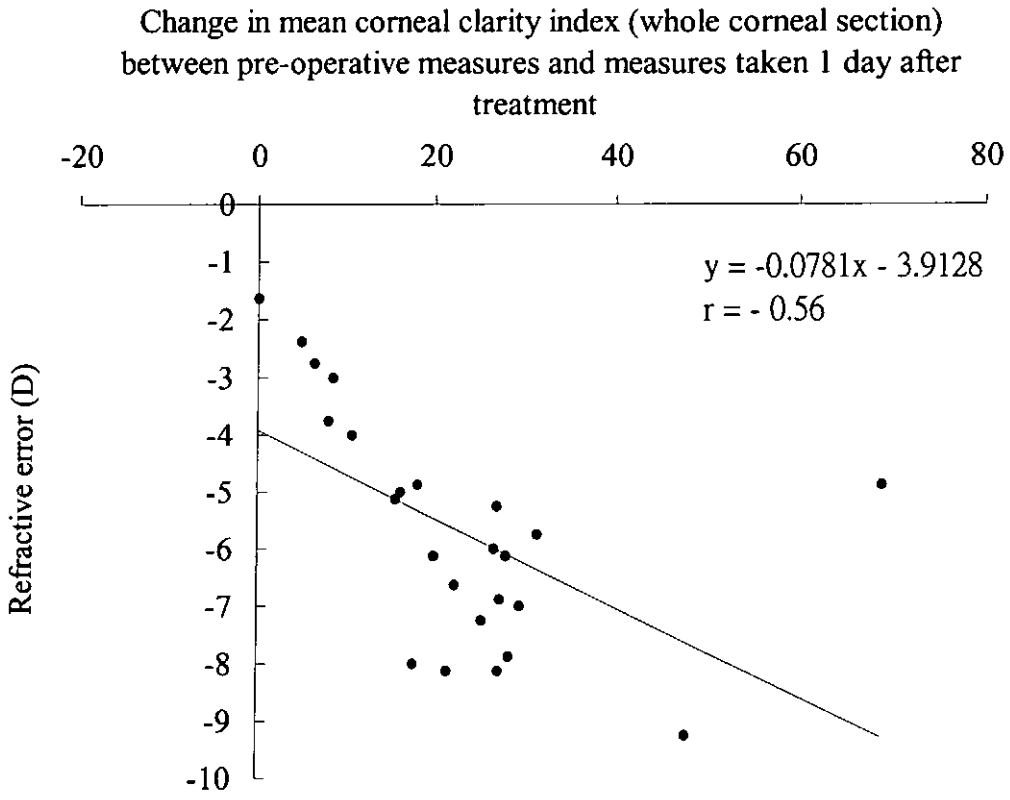


Fig. 5.8. Relationship between refractive error and change in corneal clarity index.



5.5.6 Discussion

There were 22.31 unit (whole corneal section) and 28.97 unit increases (within central 3 mm of the section) in central corneal clarity indexes one week after treatment. From the calibration curve, the central portion of the cornea will have about 17% decrease in light transmission one day after treatment. Although the central clarity index one month after LASIK has not returned to pre-LASIK value, the difference is small (4 units, about 3% drop of light transmission). Looking at the clarity index change for the whole corneal section and the trend of the results, the

clarity index tended to return to the pre-treatment level, but had not done so one month post-treatment.

Although reports have shown that there is less corneal haze due to corneal light scattering after LASIK treatment than following PRK (Jain et al., 1995; Chang et al., 1998), corneal light scattering due to corneal haze does occur.

5.5.6.1 Corneal edema

There are many possible causes of increased corneal light scattering. Any factor, for example corneal edema, that alters corneal transparency will increase corneal scattering. Corneal edema may be caused by high intra-ocular pressure, trauma, dystrophy or epithelial damage (Pavan-Langston, 1996). The accumulation of fluid inside the cornea causes swelling of the collagen fibers, and this breaks down the relationship between fiber diameter and the wavelength of light. As a result, corneal light scattering increases (Goldman and Benedek, 1967; Goldmann et al., 1968; Smith and Frame, 1969; Smith, 1970; Cox et al., 1970; Farrel et al., 1973).

The most likely causes of corneal edema after LASIK treatment in this study was

the wound healing inflammatory response. Although the preservation of the epithelium may minimize the activation of wound healing processes in corneal stroma (Jain et al., 1995), some healing processes have to take place. Pallikaris et al. (1990) found mild corneal haze three days after LASIK treatment, with progressive improvement over one month. Their findings were supported by those of the present study.

In the present study, corticosteriods were used after LASIK treatment (Chapter 2). Corticosteriods are an effective form of therapy. When corneal edema is a result of inflammation they suppress the host's natural defense systems and slow down the inflammatory response. The use of that agent probably explains why only mild haze was detected after LASIK treatment.

5.5.6.2 Stromal bed interface

Under slit-lamp bio-microscopy with 10X magnification or above and high light intensity, circular interfaces were observed located in the stroma of the corneas after LASIK treatment. This interface was still transparent and looked like mild folding in the stromal layer. It had disappeared by the first month visit in all the

subjects. As stromal tissues had been removed, a wound was formed and time was needed for the collagen fibers to reorganize. This feature must have increased light scattering after LASIK treatment, as it could be seen (light rays were reflected or scattered back after passing through it).

5.5.6.3 Dry eye

Another possible cause of corneal edema after LASIK treatment is dry eye. Aras et al. (2000), Carpel et al. (2000) and Lee et al. (2000) found that the tear secretion decreased after LASIK treatment. This is possibly due to a decrease in corneal sensitivity after LASIK treatment as corneal nerves are cut during the procedure (Kauffmann et al., 1996; Kim and Kim, 1999; Linna et al., 1998). The tear secretion reflex is reduced and as less tears are produced, the oxygen supply to the cornea will also decrease. Hypoxia might occur as well as edema. Moreover, mucous discharge is also associated with dry eye and mucous in the tear film would increase light scattering. The corneal section imaging method analyzed the whole corneal section including the tear film layer, so mucous in the tears would increase the corneal clarity index. The subjects in the present study were all given artificial tear preparations (Tear Natural II or Tear Natural III) after the treatment and were asked

to apply it at regular time intervals as mentioned in Chapter 1. Artificial tears should relieve any corneal edema due to dry eye. Therefore, while corneal edema due to dry eye is a possible cause of reduced corneal clarity it is unlikely to have occurred in this study.

5.5.6.4 Corneal thickness change after LASIK and the corneal clarity index

Applying the Munnerlyn formula mentioned in section 1.11, an 8 D ablation and a 2 D ablation will be equal to 96 μm and 24 μm reduction in corneal thickness respectively. Assuming a central corneal thickness of 550 μm, there will be approximately 17% and 4% decrease in corneal thickness after surgery for an 8 D and a 2 D myope respectively.

The reduction in corneal thickness should decrease the corneal clarity index obtained (i.e. increase corneal clarity) because the tissues that scatter and reflect light rays are reduced. However, the more the corneal tissue removed, the more the corneal insult. The greater the insult, the more the resultant light scatter and this will cause an increase in corneal clarity index (i.e. a decrease in corneal clarity). The reduction in corneal thickness and the degree of edema induced by LASIK

would counteract each other, at least initially. Once the edema has subsided, an increase in corneal clarity might be expected.

The results of the present study showed that the effect of edema outweighed the effect of thinning the cornea over the time period investigated. If the thinning of the cornea was taken into account in analyzing the results the effect of LASIK on corneal clarity would be greater.

5.5.6.5 Relationship between corneal clarity change, refractive error and visual acuity

The correlation between refractive error before LASIK and the corneal clarity index change following LASIK ($r = -0.56$), showing that approximately 31% of the variation in the change in corneal clarity index could be explained by the variation in refractive error.

The poor correlation between the change in best-corrected visual acuity and change in corneal clarity index after treatment indicated that the haze formation after LASIK did not affect visual acuity. Since high contrast texts were used in visual

acuity testing, small amount of haze would not reduce the measured acuity. Low contrast targets might show an effect, and mild corneal haze formation is likely to have been one of the reasons for decrease contrast sensitivity found in Experiment 2.

5.5.6.6 Scope for improvement

In the present study, corneal clarity was determined objectively using widely-available clinical equipment. There is, however, scope to improve the test. For example, the reading of corneal clarity obtained is instrument-dependent. The baseline value will vary according to the slit-lamp used. The corneal clarity index calculated is affected by ambient room light and therefore, the lighting conditions must be fixed in order to compare the results. It is relatively easy to control lighting in a single clinical space or laboratory, but measures are unlikely to be reproducible between laboratories. In this method, the size of the area of cornea measured is fixed, however the location of that area may vary. This is less of a problem when the clarity of the cornea is fairly evenly reduced, as shown by the high level of repeatability obtained here. It may, however, present problems if clarity is reduced unevenly and good control of subject fixation is important under these conditions.

5.5.7 Conclusions

Corneal clarity change is one of the major concerns of refractive surgery. The present experiment evaluated the effect of LASIK on corneal clarity using a quantitative method. Measurements were carried out before and for one month after LASIK. Corneal clarity decreased after LASIK treatment and there was a tendency of this value to recover more or less than a period of about one month. The effects seem likely to be due to stromal and epithelial edema caused by the normal healing process. The haze noted was very subtle and did not affect best-corrected visual acuity. LASIK does decrease corneal clarity but recovery is rapid.

Chapter 6

Summary and conclusions

6.1 Refractive error and LASIK

The present study used standardized clinical refraction methods to measure refractive error. ***The mean spherical equivalent refractive error of the subjects (Experiment 2) before LASIK was –6.03 (SD 2.28) D. Refractive error took six months to one year to stabilize to a value of –0.30 (SD 0.48) D. LASIK was therefore effective in the reduction of myopia.***

6.2 Contrast sensitivity study

6.2.1 Repeatability of the contrast sensitivity tests

Two contrast sensitivity function test methods, 2 alternative forced choice (2AFC) and Yes-No (Y-N), were compared in terms of repeatability and subject reaction to

the tests.

Repeatability values and the questionnaire results showed that the Y-N method was preferred. The repeatability value of the test method was 0.0981 log unit, indicating that an individual change can be assumed to be real if it is greater than 0.1 units.

6.2.2 Contrast sensitivity before and after LASIK

The changes in visual functions after LASIK are believed to be subtle, and may not be identifiable by tests of high contrast visual acuity. Other visual tests, for example, contrast sensitivity measurement, have proven useful in detecting visual disorders that have evaded detection by the usual acuity tests. The aim of this part of the study was to evaluate the effect of LASIK on contrast sensitivity. Measurements were carried out before and after LASIK treatment and subjects were followed for a year after the treatment. The contrast sensitivities before and after LASIK were than compared to identify and characterize any adverse effect of LASIK.

There was a general depression of contrast sensitivity after LASIK treatment..

Contrast sensitivity took at least six months to recover to the pre-operative level.

This non-permanent depression is probably related to optical factors.

6.3 Glare sensitivity

6.3.1 The effectiveness of the glare tester

A glare tester was developed using a tearscope as a glare source in Experiment 3, the sensitivity and repeatability of this newly designed glare tester were determined.

The glare tester was able to show effects of glare on contrast sensitivity. Effects were apparent in the low-to-intermediate spatial frequency region. This tester was used in Experiment 4 to evaluate the effect of LASIK on glare sensitivity.

6.3.2 Glare sensitivity before and after LASIK

Glare sensation is a common aftermath of photorefractive surgery. The aim of this part of the study was to determine the effect of LASIK on glare sensation quantitatively using the glare test developed. Measurements were carried out before

and after the treatment and all the subjects were followed for one year. In addition, a questionnaire was used to obtain information on the sensation of glare after treatment. The effect of LASIK on glare sensation was determined by comparing the differences in contrast sensitivity without and with glare at different time intervals. Also, the time for recovery of contrast sensitivity under glare was found.

There was no statistically significant difference in the reduction in CS in the presence of glare after LASIK treatment compared with before the treatment. Subjective glare sensation was experienced immediately post-operatively, however this had decreased just one day post-surgery. This negative result may be because pupil miosis under the glare condition reduced the diffracted and scattering light from the peripheral area of the LASIK treatment zone.

6.4 Corneal clarity

6.4.1 Sensitivity of two objective methods for corneal clarity measurement

Corneal clarity is usually determined clinically by subjective grading, however for research purposes, an objective and reliable method is needed. The aim of this part

of the study was to develop an objective, sensitive and reliable method to measure corneal clarity. Two methods, a Purkinje image method and a corneal section imaging method were compared.

Both tests methods were repeatable. The corneal section imaging method was more sensitive than the other, in that it could identify smaller changes in corneal clarity. Under these circumstances, the corneal section imaging method was used in determining the effect of LASIK on corneal clarity.

6.4.2 Corneal clarity before and after LASIK

Previous studies showed that the cornea after LASIK is usually quiet and stable however the relationship between corneal clarity and LASIK is still not well established. The aim of the study was to measure corneal clarity objectively before and after LASIK treatment, in order to determine to what extent corneal clarity is affected by LASIK and how the cornea recovers in the period immediately following surgery.

Corneal clarity (as determined from the complete optic section and central 3 mm of the section) decreased after LASIK treatment and had recovered to pre-treatment levels one month post-treatment. The haze noted was very subtle and would be unlikely to affect best-corrected visual acuity.

6.5 Problems encountered

The main difficulty encountered in this study was the duration of the contrast sensitivity test, and naïve observer tended to find it tedious. Some subjects commented that the tests were too long even if they lasted less than ten minutes. Although much work was done to keep the subjects interested throughout the study, a number were lost to observation because of the test duration.

Problems obtaining the software to run the contrast sensitivity test delayed progress somewhat.

6.6 Improvements to design

Use of a mydriatic agent to fix the pupil would have provided more control over retinal luminance.

The highest spatial frequency used in the contrast sensitivity test in the present study was 20.5 cpd. However, this is not high enough to equate to very fine detail (visual acuity of logMAR 0.0 is broadly equivalent to 30 cpd in spatial frequency). Spatial frequency can be increased by increasing the viewing distance (the maximum viewing length for the laboratory space available was utilized in this study). If it had been possible to double the viewing length to 2 m, the highest spatial frequency tested would also have been doubled. A decision would have had to be made whether to increase the duration of the test, or delete one of the other spatial frequencies tested.

About 9% of Chinese have myopia of more than 5 D (Wong et al., 2000) and local ophthalmologists would be interested in the effects of LASIK in higher myopes. The range of spherical equivalent errors in the present study was from –2.75 D to –11.63 D.

6.7 Further work

Refractive surgery is frequently carried out on patients with myopia of more than 12 D (Peyman, 1996; Salah et al., 1996; Pesando et al., 1997). It is likely that the effects of LASIK on the aspects of vision reported here will be greater in such highly myopic individuals than found in the present study. Further work is required to investigate this.

LASIK is a relatively new procedure and improvements to the technique can be expected, especially in the light of the development of wavefront technology. The test methods developed and used in the present study can be used to quantify the benefits gained from such advances.

6.8 Final conclusions

LASIK is an effective surgical alternative for the reduction of moderate myopia. LASIK causes a temporary decrease in contrast sensitivity (for 6 months to 1 year) and corneal clarity (for more than 1 month), and a sensation of glare (for about 1 day only).

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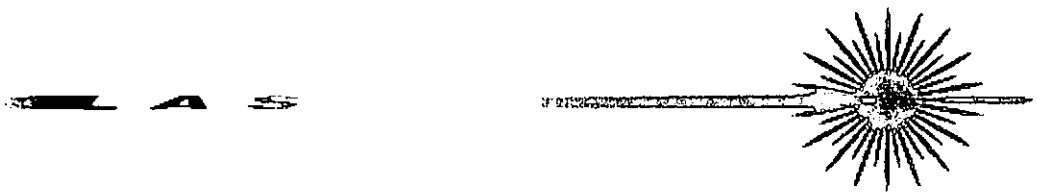
Appendix 1

Visual acuity measurement



A1.1 Introduction

Visual acuity measurement is a basic and universally employed visual assessment that provides information of how well a person recognizes high contrast detail, as represented by optotypes of various designs. The end point of visual acuity measurement may vary from examiner to examiner, or even from test to test with the same examiner, and a standardized protocol must be used in order to reduce such a variation. This appendix describes such a protocol, followed by all vision and visual acuity measurements carried out in this study.

A1. 2 Protocol

A Bailey-Lovie chart was used and placed three meters in front of the subject. The luminance level of the chart was adjusted to approximately 150 lux (Long and Woo,

1980) using external light sources. The present author carried out all the measurements. The non-examined eye was occluded, and the subject was required to read at least one full line before reaching a line where letters were misread. Subjects were asked to guess if unsure of any letter. The test was terminated when fewer than three letters were read correctly on a particular line. (Brown and Yap, 1995). Each letter correctly identified was given a logMAR score of 0.02 (Kitchin and Bailey, 1981).

Measurements were carried out according to the schedules of the different experiment undertaken (please refer to the experiments). VA measures were carried out prior to any other manipulation or assessment.

A1.3 Results

Table A1.1 summarizes the mean visual acuity of the subjects in different experiments.

Table A1.1. Mean visual acuities of the subjects

Visits	Visual acuity, [logMAR, (SD)]					
	Experiment 2		Experiment 4		Experiment 6	
	Unaided	Aided	Unaided	Aided	Unaided	Aided
Pre-operative		0.01 (0.05)		0.01 (0.06)		0.01 (0.03)
1 day					0.09 (0.13)	0.04 (0.12)
1 week	0.13 (0.14)	0.06 (0.1)	0.14 (0.16)	0.07 (0.11)	0.10 (0.10)	0.03 (0.10)
1 month	0.11 (0.14)	0.02 (0.07)	0.13 (0.16)	0.03 (0.08)	0.08 (0.11)	0.02 (0.10)
3 months	0.10 (0.14)	0.01 (0.06)	0.12 (0.17)	0.02 (0.07)		
6 months	0.09 (0.17)	0.00 (0.03)	0.11 (0.21)	0.00 (0.04)		
1 year	0.09 (0.16)	0.00 (0.03)	0.11 (0.20)	0.00 (0.03)		

Appendix 2

Subjective refraction

A2. 1 Introduction

The goal of refractive surgery is to reduce refractive error, the success of the procedure being largely defined by the extent to which it does this.

The result of subject refraction measurement may vary from test to test, even for the same examiner, and use of standardized refraction end-points helps to maximize intra-examiner reliability.

A2. 2 Methodology

Subjective refraction was carried out by the optometrist in HKLEC. A projected acuity chart was used with a mirror reflecting system so that the viewing distance of the chart was 6 m. The end point of the test was that the circles on the duochrome test were "equally clear". If this could not

be achieved, the circles on red were left clearer. The spherical equivalent of the refractive error was used to quantify refractive error.

A2.3 Results

Table A2.1 summarizes the spherical equivalent power of the subjects in different experiments.

Table A2.1. Spherical equivalent power of the subjects

Visit	Spherical equivalent power [D, (SD)]		
	Experiment 2	Experiment 4	Experiment 6
Pre-operative	–6.03 (2.28)	–6.21 (2.51)	–5.66 (2.02)
1 day			–0.05 (0.40)
1 week	+0.02 (0.42)	+0.04 (0.47)	–0.14 (0.36)
1 month	–0.07 (0.45)	–0.11 (0.47)	–0.27 (0.43)
3 months	–0.20 (0.46)	–0.28 (0.48)	
6 months	–0.32 (0.51)	–0.45 (0.59)	
1 year	–0.3 (0.48)	–0.41 (0.57)	

Appendix 3

Learning effect of the contrast sensitivity test

A3.1 Introduction

The contrast sensitivity after LASIK treatment recovered with time (Experiment 2). It is possible that a learning effect contributes to that change.

A3.2 Aim

To investigate the learning effect associated with the contrast sensitivity test used in this study.

A3.3 Methodology

Four observers, mean age 21.5 (SD 0.58) years, were recruited. They were requested to attempt the test on three different days, the second day being one week after the first day, and the third day three weeks later. The contrast

sensitivity test used was the same as in Experiment 2. All the subjects had aided binocular visual acuity of logMAR 0.0 or better. The contrast sensitivity test was carried out binocularly in this experiment (please refer to Chapter 3, Section 3.2.5 for the test procedure). The procedure to be carried out was explained to the subject, who was given the opportunity to ask questions. No subject had prior experience of the VSG contrast sensitivity test.

The contrast sensitivities for different spatial frequencies were averaged so that a mean contrast sensitivity value was obtained for each subject, one value for each of the three trials.

A3.4 Results

The result of the contrast sensitivity of the subjects are summarized in the Table A3.1. and Fig. A3.1.

A4.5 Conclusion

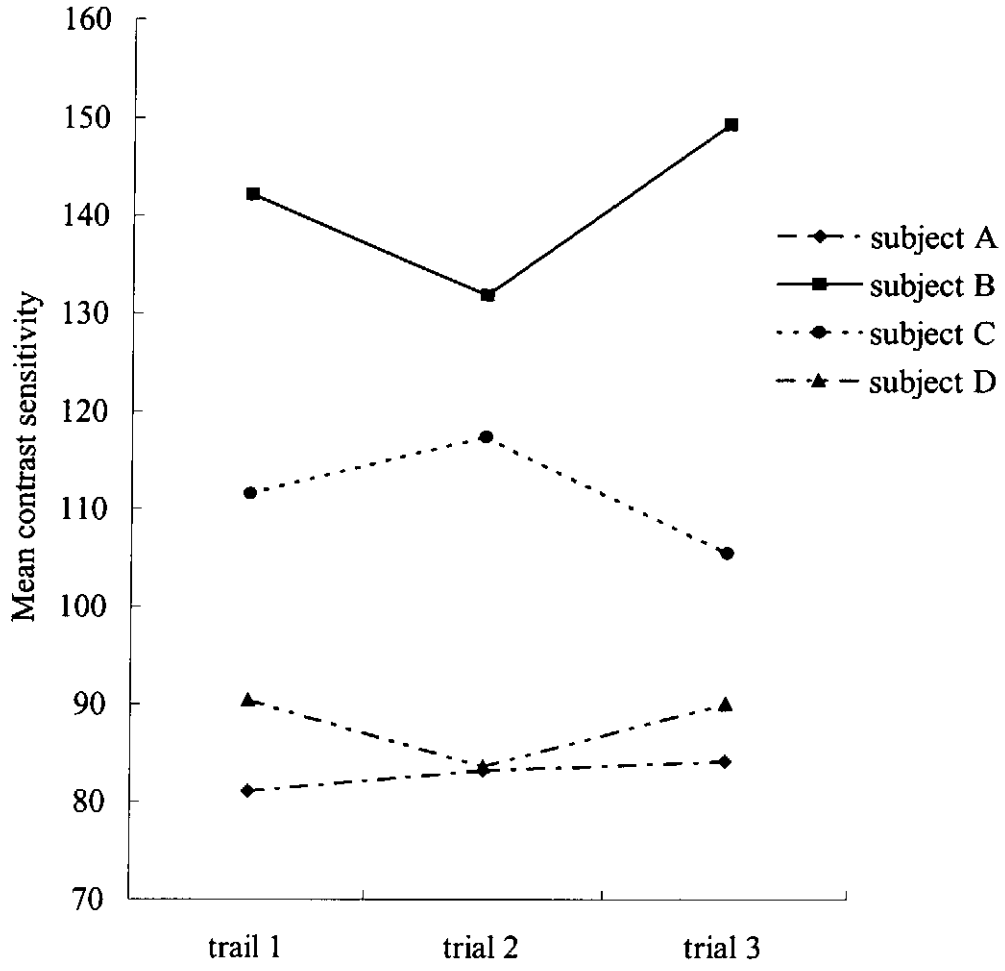
Fig A3.1 shows no trend which is suggestive of a learning effect. Therefore, it is concluded that there was no learning effect on the recovery of contrast sensitivity

after LASIK treatment.

Table A3.1. The contrast sensitivity values for each spatial frequency and the mean value for each of the three trials.

		Contrast sensitivity in different spatial frequencies							
		0.3	0.8	1.5	3.4	6.9	10.3	20.5	Mean
Subject A	Trial 1	31.6	141	141	141	79.4	31.6	2.2	81.114
	Trial 2	31.6	141	141	141	79.4	44.7	3.4	83.157
	Trial 3	44.7	141	141	141	79.4	31.6	10	84.1
Subject B	Trial 1	79.4	79.4	355	355	79.4	44.7	2.2	142.16
	Trial 2	79.4	79.4	278	355	89.1	31.6	10	131.79
	Trial 3	79.4	121	224	355	178	79.4	8	149.26
Subject C	Trial 1	79.4	141	355	141	44.7	17.8	2.2	111.59
	Trial 2	79.4	141	355	178	44.7	17.8	5.6	117.36
	Trial 3	79.4	141	278	141	79.4	17.8	1.4	105.43
Subject D	Trial 1	79.4	141	141	200	44.7	25.1	1.4	90.371
	Trial 2	79.4	141	141	141	56.2	25.1	1.6	83.614
	Trial 3	79.4	141	141	200	44.7	22.4	1.4	89.986

Fig. A3.1. The mean contrast sensitivity values for each of the three trials.



Appendix 4

Numerical results

A4.1 Repeatability test of the Y-N and 2AFC method

The mean contrast sensitivities obtained by Y-N method and 2AFC method in Experiment 1 are summarized in Table A4.1.

Table 4.1. The mean contrast sensitivities for different spatial frequencies obtained in Experiment 1. Values in blankets show 1 SD.

	Contrast sensitivity									
Spatial frequency (cpd)	0.3	0.8	1.5	3.4	5.1	6.8	8.2	10.3	13.7	20.5
Y-N	36.58 (7.83)	97.73 (18.40)	159.40 (45.64)	279.95 (102.42)	197.34 (92.43)	112.41 (39.50)	68.85 (26.67)	35.28 (17.63)	14.84 (6.35)	3.78 (2.30)
2AFC	37.24 (7.17)	111.87 (27.90)	177.40 (44.04)	294.20 (86.68)	213.90 (88.36)	126.90 (36.10)	62.39 (23.65)	31.22 (9.54)	15.66 (6.75)	3.89 (1.42)

A4.2 Contrast sensitivity before and after LASIK

The mean contrast sensitivities for different spatial frequencies in Experiment 2 are summarized in Table A4.2.

Table A4.2. The mean contrast sensitivities for different spatial frequencies before and after LASIK treatment. Values in blankets show 1 SD.

	Contrast sensitivity						
Spatial frequency (cpd)	0.3	0.8	1.5	3.4	6.9	10.3	20.5
Before LASIK	45.89 (23.42)	118.17 (59.17)	224.29 (119.87)	228.95 (119.47)	121.80 (70.11)	43.28 (26.14)	7.14 (6.76)
1 week after	33.01 (24.86)	80.50 (46.73)	134.56 (93.18)	136.37 (90.38)	75.04 (56.07)	27.95 (20.48)	4.23 (3.62)
1 month after	33.49 (24.57)	84.50 (51.44)	142.47 (98.45)	143.89 (92.77)	74.79 (52.27)	27.68 (20.84)	4.09 (3.33)
3 month after	37.20 (22.45)	93.01 (46.01)	159.68 (97.39)	178.34 (109.33)	93.93 (68.49)	35.14 (25.00)	4.88 (4.38)
6 month after	41.97 (19.09)	115.85 (57.49)	192.50 (105.18)	211.35 (117.38)	114.00 (73.71)	37.94 (22.39)	4.70 (3.34)
1 year after	44.09 (21.41)	119.53 (58.57)	219.00 (114.32)	223.07 (114.52)	119.20 (70.06)	41.18 (26.03)	6.02 (5.60)

A4.3 Effectiveness of the newly designed glare tester

The mean contrast sensitivities for different spatial frequencies with and without glare in Experiment 3.

Table A4.3. Contrast sensitivity with and without glare. Values in blankets show 1 SD.

	Contrast sensitivity						
Spatial frequency (cpd)	0.3	0.8	1.5	3.4	6.9	10.3	20.5
Without glare (SD)	36.51 (17.40)	109.39 (30.90)	203.75 (82.28)	271.62 (67.69)	104.09 (66.31)	29.39 (20.62)	3.69 (2.36)
With glare (SD)	28.58 (21.31)	65.24 (29.25)	86.76 (40.12)	68.05 (42.46)	45.36 (22.43)	23.03 (11.30)	2.76 (2.20)

A4.4 Glare sensitivity before and after LASIK

The mean differences of contrast sensitivities for different spatial frequencies with and without glare in Experiment 4 are summarized in Table A4.4.

Table A4.4. The mean differences of contrast sensitivities with and without glare. Values in blankets show 1 SD.

	Mean difference of contrast sensitivity without and with glare						
Spatial frequency (cpd)	0.3	0.8	1.5	3.4	6.9	10.3	20.5
Pre-operative	15.3 (11.20)	44.03 (22.04)	84.08 (65.34)	74.93 (50.35)	46.54 (51.58)	16.34 (15.57)	2.80 (3.64)
1 week	16.18 (10.40)	42.91 (18.01)	64.19 (32.53)	74.57 (41.19)	45.07 (46.38)	16.50 (15.10)	2.66 (3.57)
1 month	15.43 (8.35)	40.68 (17.44)	60.94 (32.25)	74.11 (46.74)	44.21 (46.51)	16.14 (15.14)	2.46 (3.67)
3 months	17.34 (8.45)	47.34 (19.07)	74.70 (45.62)	78.26 (47.70)	47.16 (49.22)	16.92 (14.71)	2.99 (4.61)
6 months	17.09 (8.77)	48.91 (19.63)	85.94 (64.96)	80.00 (45.02)	48.50 (50.14)	18.35 (14.98)	2.63 (2.82)
1 year	16.88 (8.40)	45.98 (19.25)	85.05 (61.55)	78.07 (44.07)	49.49 (49.40)	18.14 (14.94)	2.56 (2.87)

Appendix 5

Information sheets

A5.1 Information sheet for Experiment 1 - repeatability of 2 Alternative Forced Choice method and Yes-No method of measuring contrast sensitivity function

I am a Master degree student in the Department of Optometry and Radiography and I am going to measure a visual function called contrast sensitivity. Contrast sensitivity is the ability to detect brightness differences between objects or areas in space.

In this study, a brief eye examination, including vision measurement, refraction and eye health check, will be done. You will be asked to do each of the tests twice. The tests are simple. You will be asked to sit in front of a computer monitor and give responses by pushing a button. It takes less than an hour including 10

minutes break to finish all the tests. Or you can undergo the tests in two separate visits if you prefer.

No drugs of any kind will be used and there are no risks to you from this study. All data collected will be kept confidential, and you may withdraw from the study at any time should you wish to do so.

Please note that the examination carried out does not comprise a full eye examination. It will, however, help to determine if you have an eye problem for which you should have a complete eye examination.

I will be happy to answer any questions you have relating to this information sheet or the study. If you have any complaints about the conduct of this study, please contact the Secretary, Faculty of Health and Social Sciences Research Committee (Tel 27665078).

Thank you for considering taking part in our study.

Master Student investigator

Chan Wing Wo (Tel 27666122)

Chief Supervisor

Professor Marion Edwards (Tel 27666110)

A5.2 Information sheet for Experiment 2 - contrast sensitivity before and after LASIK

I am a Master degree student in the Department of Optometry and Radiography and I am going to evaluate the effect of LASIK treatment on a visual function called contrast sensitivity. Contrast sensitivity is the ability to detect brightness differences between objects or areas in space.

In this study, you will be asked to do a contrast sensitivity test. The test is simple. You will be asked to sit in front of a computer monitor and indicate whether you see a target or not by pushing button. It takes less than half an hour including 10 minutes break to finish the test.

No drugs of any kind will be used and there are no risks to you from this study. All data collected will be kept confidential, and you may withdraw from the study at any time should you wish to do so without penalty of any kind.

I will happy to answer any questions you have relating to this information sheet or the study. If you have any complaints about the conduct of the study, please contact the Secretary, Faculty of Health and Social Sciences Research Committee (Tel 27665078)

Thank you for considering taking part in out study.

Master Student investigator

Chan Wing Wo (Tel 27666122)

Chief Supervisor

Professor Marion Edwards (Tel 27666110)

A5.3 Information sheet for Experiment 3 - to determine the effectiveness of the newly designed glare tester

I am a Masters degree student in the Department of Optometry and Radiography and I wish to evaluate the effect of glare on a visual function called contrast sensitivity. Glare means a condition that will lower your visual performance. Contrast sensitivity is the ability to detect brightness differences between objects or areas in space.

In this study, I will test your contrast sensitivity while your vision is dazzled by a glare source. The test is simple. You will be asked to sit in front of a computer monitor and indicate whether you see a target or not by answering "Yes" or "No". It takes less than ten minutes, including a one minute break, to finish the test. You will then be given a five minute rest, and then the test will be repeated.

No drugs of any kind will be used and there are no risks to you from this study. All data collected will be kept confidential, and you may withdraw from the study at any time should you wish to do so without penalty of any kind.

I will be happy to answer any questions you have relating to this information sheet or the study. If you have any complaints about the conduct of this study, please contact the Secretary, Faculty of Health and Social Sciences Research Committee (Tel 27665078).

Thank you for considering taking part in our study.

Master Student investigator

Chan Wing Wo (Tel 27664463)

Chief Supervisor

Professor Marion Edwards (Tel 27666110)

A5.4 Information sheet for Experiment 4 - the effect of LASIK on glare sensitivity

I am a Master degree student in the Department of Optometry and Radiography and I am going to evaluate the effect of glare on a visual function called contrast sensitivity (CS) after LASIK treatment. Glare means a condition that will lower your visual performance. Contrast sensitivity is the ability to detect brightness differences between objects or areas in space.

In this study, you will be asked to do a CS test with a glare source. The test is simple. You will be asked to sit in front of a computer monitor and indicate whether you see a target or not by answering "Yes" or "No". It takes less than fifteen minutes, including an one minute and a two minutes breaks, to finish the test.

No drugs of any kind will be used and there are no risks to you from this study. All data collected will be kept confidential, and you may withdraw from the study at any time should you wish to do so without penalty of any kind.

I will be happy to answer any questions you have relating to this information sheet or the study. If you have any complaints about the conduct of this study, please contact the Secretary, Faculty of Health and Social Sciences Research Committee (Tel 27665078).

Thank you for considering taking part in our study.

Master Student investigator

Chan Wing Wo (Tel 27666122)

Chief Supervisor

Professor Marion Edwards (Tel 27666110)

A5.5 Information sheet for Experiment 5 - repeatability and sensitivity of two objective corneal clarity tests.

I am a Master degree student in the Department of Optometry and Radiography and I am evaluating two techniques that measure the clarity of the cornea.

In this study, you need to wear a soft contact lens to sleep and sit in front of an instrument and look at a fixation target. Some pictures of your eyes will be taken as records and for analysis. It takes 40 minutes included 30 minutes sleeping time to finish the test. No drugs of any kind will be used and there are no risks to you from this study. All data collected will be kept confidential, and you may withdraw from the study at any time should you wish to do so.

I will be happy to answer any questions you have relating to this information sheet or the study. If you have any complaints about the conduct of this study, please contact the Secretary, Faculty of Health and Social Sciences Research Committee (Tel 27665078).

Thank you for considering taking part in our study.

Master Student investigator

Chan Wing Wo (Tel 27666122)

Chief Supervisor

Professor Marion Edwards (Tel 27666110)

A5.6 Information sheet for Experiment 6 - corneal clarity change before and after LASIK treatment

I am a Masters degree student in the Department of Optometry and Radiography of The Hong Kong Polytechnic University and, I am evaluating the effect of LASIK on corneal clarity. LASIK is the most recent and popular procedure for refractive surgery. This study examines whether the clarity of the cornea, the clear front part of your eye, changes following LASIK. If the corneal clarity is reduced, we will determine how many days it takes before corneal clarity returns to normal.

In this study, we ask you to attend every day for one week after the LASIK treatment. We will simply take some photographs of your eye on the visit before the procedure and each day for a week afterwards. It will take not more than 10 minutes to take the photographs, which will then be used to calculate corneal clarity.

The test will not cause any discomfort and there is no risk to you. No drugs of any kind will be used. All data collected will be kept confidential, and you may withdraw from the study at any time, should you wish to do so.

I will be happy to answer any questions you have relating to this information sheet or the study. If you have any complaints about the conduct of this study, please contact the Secretary, Faculty of Health and Social Sciences Research Committee (Tel 27665078).

Thank you for considering taking part in our study.

Master Student investigator

Chan Wing Wo (Tel 27664463)

Chief Supervisor

Prof. Marion Edwards (Tel 27666110)

Appendix 6

Consent form for all experiments

Have you read the information sheet provided?	Yes / No
Have you had an opportunity to ask questions and discuss this study?	Yes / No
Have your received satisfactory answers to all of your questions?	Yes / No
Have you received enough information about the study?	Yes / No
Who provided the information / answered your questions	
Ms / Mr /Dr /Prof _____	
Do you understand that participation is entirely voluntary?	Yes / No
Do you understand that you are free to withdraw from the study	
• at any time	Yes / No
• without having to give a reason	Yes / No
• without affecting your future care (*as applicable*)	Yes / No
Do you agree to take part in this study	Yes / No

Name:

Signature: Date:

Witness:

Appendix 7

Raw data for experiment 2, 4 and 6

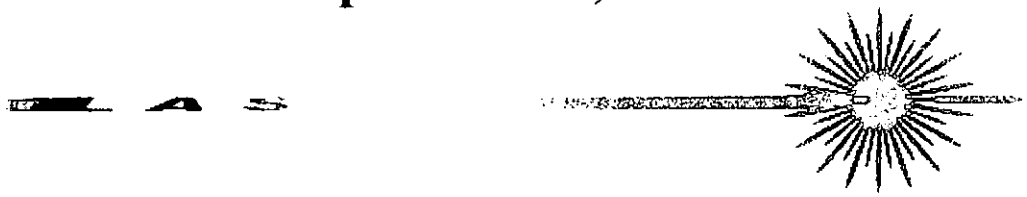


Table A7.1. Spreadsheet for Experiment 2 showing gender, age, preoperative refractive error and preoperative visual acuity of subjects.

Subject	Gender	Age	Preoperative refractive error (D)	Preoperative visual acuity (logMAR)
001*	M	26	-8.00/-0.50x120	0.08
002	F	35	-0.50/-5.50x170	0.02
003*	F	34	-6.50/-0.50x160	0.06
004	F	34	-6.50/-0.50x140	0.02
005*	F	31	-3.75/-2.25x010	0.00
006	F	26	-3.75	0.00
008*	F	36	-5.25	0.00
009*	F	35	-2.50/-2.75x005	0.04
011	M	29	-6.25/-2.50x025	0.04
012*	M	24	-11.00/-1.25x045	0.10
013	M	33	-2.50/-1.50x165	0.00
014	F	25	-5.50/-0.75x090	0.04
016	M	26	-7.50/-0.75x175	-0.06
022*	M	39	-10.00	0.00
025	M	35	-5.25/-0.75x175	0.00
027*	F	30	-2.50/-0.50x040	0.04
028	M	43	-4.00/-0.50x170	0.00
029	F	33	-4.25/-2.00x020	0.00
030*	F	34	-6.00/-2.25x155	0.10
031	F	26	-5.00	-0.04
032	F	37	-3.50/-0.50x175	-0.10
033*	M	28	-4.75/-0.50x180	0.02
034*	F	38	-2.75/-0.75x090	0.02
035*	F	31	-4.75/-0.25x180	-0.04
036*	M	26	-6.25/-0.75x020	0.00
037*	M	35	-6.25/-1.00x175	0.00
038	M	35	-5.75/-1.50x180	0.00
039	F	29	-4.00/-0.50x110	-0.02
040*	F	41	-5.00/-0.50x055	0.04
041*	F	25	-3.25/-0.75x180	-0.04
042*	M	38	-6.50/-0.25x170	-0.08
043*	F	30	-8.00/-1.75x175	0.04
044*	M	31	-4.25	-0.02
045	F	27	-10.25/-1.00x180	0.00
046*	F	29	-7.50/-1.00x180	0.02
047*	M	28	-2.75/-0.50x180	0.00
048*	F	25	-6.50/-2.75x180	0.08
049	M	33	-9.25/-2.75x020	0.16
050	F	29	-6.50/-0.75x175	-0.10
051*	F	34	-7.75	0.00
052	M	37	-3.25/-1.75x180	0.00

* Subject participated both Experiment 2 and Experiment 4.

Table A7.2. Spreadsheet for Experiment 2 and 4 showing postoperative refractive error and postoperative visual acuity of the subjects.

	1 week after			1 one month after			3 months after			6 months after			1 year after		
Subject	Refractive error	Unaided VA	Aided VA	Refractive error	Unaided VA	Aided VA	Refractive error	Unaided VA	Aided VA	Refractive error	Unaided VA	Aided VA	Refractive error	Unaided VA	Aided VA
001*	-0.50/-0.50x060	0.06	0.00	+0.50/-0.50x080	0.08	0.00	0.00/-0.50x110	0.02	0.00	0.00/-0.50x110	0.02	0.00	0.00/-0.50x110	0.02	0.00
002	+0.75/-1.25x125	0.00	0.00	+1.25/-1.00x140	0.22	-0.08	+1.00/-0.75x145	0.28	0.00	+1.00/-1.25x140	0.28	0.02	+1.00/-1.25x140	0.28	0.00
003*	+0.25/-0.50x120	0.20	0.00	-0.50/-0.25x160	0.20	0.00	-0.50/-0.25x160	0.20	0.00	-0.50/-0.25x160	0.20	0.00	-0.50/-0.25x160	0.20	0.00
004	-0.25	0.02	0.00	0.00-0.25x165	0.04	0.00	-0.25	0.02	0.00	-0.25	0.00	0.00	-0.25	0.02	0.00
005*	+0.50/-0.75x120	0.18	0.02	0.25	0.18	0.08	+0.50/-0.75x120	0.16	0.00	+0.50/-0.75x120	0.00	0.00	+0.50/-0.75x120	0.04	-0.02
006	+0.25	0.08	0.04	-0.25/-0.25x090	0.02	0.00	+0.25	0.02	0.00	0.00/-0.25x090	0.00	0.00	0.00/-0.25x090	0.00	0.00
008*	+0.75/-0.75x90	0.30	0.30	+0.50/-0.25x120	0.10	0.00	+0.25/-0.50x120	0.06	0.00	0.00/-0.75x110	-0.04	-0.06	+0.25/-0.75x110	0.04	0.00
009*	+0.50/-0.75x15	0.20	0.00	+0.25/-0.75x015	0.26	-0.04	+0.25/-0.75x015	0.10	0.00	+0.25/-0.75x015	0.10	0.00	0.00/-0.75x015	0.10	0.00
011	0.00/-0.75x30	0.28	0.28	-0.25/-0.75x060	0.30	0.02	-0.50/-0.75x040	0.30	0.00	-0.25/-1.00x035	0.22	0.00	-0.25/-1.00x035	0.22	0.00
012*	+0.75	0.32	0.26	+0.50/-0.75x180	0.20	0.00	-0.75/-0.50x010	0.42	0.00	-0.75/-1.25x180	0.64	0.00	-0.75/-1.25x180	0.64	0.00
013	0.00	0.00	0.00	0.00-0.50x180	0.00	0.00	0.00	0.04	0.04	0.00/-0.50x180	0.02	0.02	0.00/-0.50x180	0.02	0.00
014	+0.50/-0.50x90	0.10	0.10	+0.50/-0.50x090	0.04	0.00	+0.50/-0.50x090	0.04	0.00	+0.25/-0.50x090	0.00	0.00	+0.25/-0.50x090	0.00	0.00
016	+1.00/-1.00x95	-0.04	-0.04	+1.25/-1.00x095	-0.04	-0.04	+1.25/-1.00x095	0.10	0.04	+1.00/-1.00x090	0.14	0.06	+1.00/-1.00x090	0.10	0.06
022*	0.00	0.26	0.20	0.00	0.12	0.02	+0.25/-0.50x150	0.02	0.02	+0.25/-0.50x150	0.02	0.00	+0.25/-0.50x150	0.02	0.00
025	+0.25/-0.75x10	0.32	0.00	0.00/-0.75x010	0.16	-0.08	0.00/-0.50x015	0.20	0.00	0.00/-0.50x015	0.20	0.00	0.00/-0.50x015	0.20	0.00
027*	+0.00/-0.25x90	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-0.50	0.00	-0.04	-0.25/-0.25x090	0.00	-0.04
028	-0.25/-0.50x80	0.34	0.10	-0.25/-0.25x090	0.16	0.06	-0.50	0.04	0.02	-0.50	0.04	0.00	-0.50	0.02	0.00
029	+0.25	0.00	0.00	+0.25/-0.50x120	0.00	0.00	-0.25/-0.50x110	0.00	0.00	-0.25/-0.50x110	0.00	0.00	-0.25	0.00	0.00
030*	+0.25/-0.75x145	0.08	0.00	-0.50/-0.75x160	0.12	-0.06	-0.25/-0.75x155	0.06	0.02	-0.25/-0.75x155	0.06	0.02	-0.25/-0.50x155	0.02	0.02
031	-1.00	0.50	0.04	-1.00	0.54	0.00	-1.25/-0.50x020	0.28	0.00	-1.50/-0.75x005	0.22	0.00	-1.25/-0.75x005	0.22	0.00
032	+0.25	0.18	0.18	0.00	0.00	0.00	0.50/-1.00x090	0.02	-0.10	+0.25	0.00	0.00	+0.25	0.00	0.00
033*	-0.50	0.04	0.02	-0.25	0.02	0.00	-0.25	0.02	0.00	-0.50	0.02	0.00	-0.25/	0.02	0.00
034*	0.00/-0.50x40	0.18	0.10	-0.25/-0.50x040	0.30	0.00	-0.25/-0.50x040	0.28	0.00	-0.25/-0.50x040	0.08	0.00	-0.25/-0.50x040	0.08	0.00
035*	+0.50/-0.75x160	0.04	-0.06	+0.25/-0.50x160	0.04	-0.06	+0.25/-0.50x160	0.04	-0.06	0.25/-0.50x160	0.04	-0.04	+0.25/-0.50x160	0.04	-0.04
036*	+0.25/-0.50x085	0.02	0.00	+0.25/-0.50x090	0.06	0.06	0.00	0.06	0.06	-0.25	0.06	0.00	-0.25	0.06	0.00
037*	+0.75/-0.50x075	0.10	0.04	+0.50/-0.25x075	0.06	0.04	+0.50	0.02	0.02	+0.25	0.02	0.02	+0.25	0.02	0.02
038	+0.75	0.06	0.04	0.50	0.06	0.06	+0.25	0.02	0.02	0.00/-0.25x095	0.02	0.02	0.00/-0.25x095	0.00	0.00
039	0.00/-0.50x130	0.00	0.00	-0.25/-0.50x140	0.06	0.00	0.00	-0.06	-0.06	0.00/-0.50x120	0.02	-0.06	0.00/-0.50x120	0.02	-0.06
040*	+0.75/-0.50x120	0.04	0.16	+0.75/-0.50x110	0.04	0.22	0.00/-0.50x105	0.08	0.00	0.00/-0.50x105	0.02	-0.02	0.00/-0.50x105	0.02	-0.02
041*	0.00/-0.50x010	-0.04	-0.04	-0.25/-0.25x010	0.00	0.00	0.00/-0.50x010	0.10	0.00	0.00/-0.50x030	0.22	0.00	0.00/-0.50x030	0.10	0.00
042*	+0.50/-0.50x120	0.10	0.00	+0.25/-0.50x120	0.02	0.02	0.00/-0.50x120	0.16	0.02	-0.25/-0.50x020	0.16	0.00	-0.25/-0.50x020	0.12	0.00
043*	-0.50/-0.50x065	0.10	0.04	-0.50/-0.50x065	0.10	0.04	-0.50/-0.25x060	0.08	0.04	-0.25/-0.25x065	0.02	0.00	-0.50	0.04	0.02
044*	+1.00	0.10	0.02	+0.75/-0.25x160	0.10	0.00	+0.50/-0.50x160	0.00	0.00	+0.50/-0.25x160	0.00	0.00	+0.50/-0.25x160	0.00	0.00
045	-0.25/-0.25x130	0.30	0.28	-0.75/-0.25x180	0.30	0.10	-0.25/-0.50x180	0.02	0.00	-0.25/-0.50x180	0.02	0.00	-0.25/-0.50x180	0.02	0.00
046*	0.00	0.02	0.00	+0.25	0.00	0.00	0.00/-0.25x070	0.00	0.00	0.00/-0.25x070	0.00	0.00	0.00/-0.25x070	0.00	0.00

Table A7.2 (continued)

047*	+0.50	0.04	0.02	+0.50	0.02	0.02	+0.25	0.00	0.00	+0.25	0.00	0.00	+0.25	0.00	0.00
048*	+0.50/-0.75x090	0.20	0.18	+0.25/-0.75x095	0.28	0.08	+0.25/-0.75x105	0.16	0.12	+0.25/-0.75x100	0.16	0.14	+0.25/-0.75x100	0.08	0.10
049	+0.75/-0.75x160	0.54	0.30	+0.50/-0.50x170	0.50	0.30	-1.00/-0.50x175	0.72	0.30	-1.50/-0.75x180	0.80	0.08	-1.50/-0.75x180	0.80	0.08
050	0.00	0.02	0.00	0.00	-0.06	-0.06	0.00/-0.50x130	0.02	0.00	-0.25	-0.02	-0.04	-0.25	-0.02	-0.04
051*	0.00/-0.25x030	0.02	0.00	0.00/-0.50x170	0.02	0.00	0.00/-0.50x160	0.06	-0.02	-0.25/-1.25x160	0.12	0.00	-0.25/-1.25x160	0.10	0.00
052	-0.25/-0.25x085	0.02	0.02	-0.25/-0.25x085	0.02	0.00	-0.25	0.02	0.00	-0.25	0.00	0.00	-0.25	0.00	0.00

* Subject participated both Experiment 2 and Experiment 4.

Table A7.3a. Spreadsheet for Experiment 2 showing contrast sensitivity before and after LASIK.

	0.3 cpd						0.8 cpd						1.5 cpd						3.4 cpd					
Subjects	1st	2nd	3rd	4th	5th	6th	1st	2nd	3rd	4th	5th	6th	1st	2nd	3rd	4th	5th	6th	1st	2nd	3rd	4th	5th	6th
001*	31.6	14.1	14.1	22.4	31.6	31.6	44.7	22.4	22.4	31.6	44.7	44.7	79.4	31.6	31.6	44.7	63.5	63.5	79.4	31.6	31.6	44.7	63.5	79.4
002	50.1	66.8	56.2	66.8	59.6	59.6	158.0	168.0	178.0	178.0	178.0	178.0	282.0	251.0	316.0	316.0	355.0	316.0	335.0	335.0	266.0	447.0	422.0	422.0
003*	31.6	20.0	20.0	31.6	31.6	31.6	56.2	33.5	24.4	33.5	56.2	56.2	100.0	42.2	56.2	70.8	100.0	100.0	251.0	141.0	155.0	200.0	240.0	240.0
004	89.1	53.1	39.8	56.2	89.1	89.1	335.0	168.0	119.0	133.0	335.0	335.0	398.0	282.0	199.0	178.0	199.0	355.0	422.0	299.0	266.0	376.0	376.0	398.0
005*	39.8	35.5	33.5	35.5	35.5	35.5	94.9	94.4	75.0	75.0	75.0	75.0	150.0	141.0	119.0	141.0	199.0	119.0	240.0	200.0	216.0	216.0	216.0	188.0
006	35.5	37.6	35.5	35.5	37.6	37.6	89.1	66.8	59.6	59.6	66.8	66.8	119.0	89.1	54.1	89.1	89.1	119.0	100.0	84.1	84.1	84.1	100.0	100.0
008*	33.5	15.8	17.8	17.8	31.6	26.6	106.0	59.6	53.1	59.6	106.0	75.0	158.0	126.0	133.0	133.0	126.0	168.0	200.0	133.0	141.0	150.0	200.0	178.0
009*	56.2	35.5	35.5	44.7	56.2	56.2	119.0	79.4	100.0	100.0	119.0	119.0	355.0	251.0	251.0	355.0	355.0	355.0	355.0	251.0	251.0	355.0	355.0	355.0
011	112.0	106.0	106.0	106.0	84.1	106.0	251.0	178.0	200.0	178.0	150.0	224.0	422.0	316.0	355.0	422.0	422.0	422.0	316.0	200.0	266.0	316.0	335.0	316.0
012*	70.8	47.3	47.3	53.1	53.1	66.8	158.0	84.1	84.1	89.1	89.1	141.0	316.0	112.0	112.0	141.0	178.0	316.0	335.0	112.0	112.0	178.0	200.0	316.0
013	56.2	47.3	44.7	53.1	56.2	56.2	150.0	119.0	141.0	141.0	178.0	150.0	200.0	237.0	355.0	316.0	355.0	237.0	355.0	266.0	299.0	299.0	237.0	355.0
014	79.4	44.7	75.0	75.0	75.0	75.0	126.0	100.0	126.0	100.0	126.0	126.0	224.0	150.0	158.0	158.0	178.0	224.0	150.0	94.4	112.0	112.0	150.0	150.0
016	20.8	10.6	20.8	20.8	20.8	20.8	100.0	89.1	94.4	126.0	100.0	100.0	139.0	126.0	126.0	141.0	139.0	139.0	100.0	79.4	94.4	89.1	126.0	126.0
022*	75.0	66.8	66.8	66.8	53.1	66.8	168.0	141.0	150.0	158.0	133.0	141.0	299.0	168.0	188.0	178.0	168.0	282.0	355.0	199.0	282.0	335.0	335.0	355.0
025	31.6	22.4	23.7	23.7	31.6	31.6	65.8	44.7	44.7	44.7	65.8	65.8	100.0	84.1	89.1	89.1	89.1	100.0	139.0	94.4	89.1	94.4	139.0	139.0
027*	31.6	20.8	20.8	31.6	31.6	31.6	100.0	56.2	56.2	65.8	89.1	100.0	158.0	100.0	100.0	100.0	100.0	139.0	139.0	56.2	100.0	112.0	112.0	100.0
028	70.5	84.1	59.6	56.2	70.5	70.5	150.0	133.0	133.0	150.0	168.0	150.0	531.0	422.0	224.0	237.0	355.0	422.0	531.0	355.0	316.0	237.0	531.0	422.0
029	56.2	22.4	33.5	56.2	56.2	56.2	100.0	75.0	89.1	100.0	100.0	100.0	178.0	141.0	168.0	178.0	168.0	178.0	316.0	200.0	299.0	316.0	316.0	316.0
030*	31.6	22.4	34.4	39.8	34.4	34.4	141.0	89.1	84.1	100.0	141.0	141.0	251.0	133.0	141.0	141.0	178.0	237.0	251.0	178.0	237.0	251.0	237.0	237.0
031	56.2	22.4	22.4	22.4	50.1	50.1	100.0	50.1	84.1	100.0	100.0	100.0	200.0	94.9	133.0	141.0	178.0	200.0	141.0	112.0	100.0	100.0	112.0	141.0
032	59.6	106.0	106.0	84.1	70.8	70.8	224.0	178.0	178.0	200.0	211.0	211.0	335.0	282.0	355.0	376.0	355.0	335.0	398.0	251.0	299.0	376.0	376.0	376.0
033*	22.4	17.8	17.8	17.8	22.4	22.4	39.8	33.4	23.7	23.7	33.4	39.8	100.0	42.2	33.4	33.4	56.2	70.8	100.0	56.2	42.2	56.2	79.4	100.0
034*	40.1	35.5	35.5	34.4	40.1	40.1	50.1	44.7	44.7	50.1	50.1	50.4	94.4	65.8	70.8	70.8	70.8	94.4	94.4	65.8	70.8	70.8	94.4	94.4
035*	25.1	20.0	25.1	22.4	25.1	25.1	79.4	79.4	79.4	79.4	79.4	79.4	141.0	94.4	141.0	141.0	141.0	141.0	141.0	94.4	112.0	112.0	112.0	141.0
036*	22.4	17.8	17.8	17.8	22.4	22.4	50.1	34.4	44.7	44.7	56.2	56.2	79.4	63.1	79.4	79.4	79.4	79.4	79.4	56.2	63.1	63.1	79.4	79.4
037*	44.7	22.4	22.4	22.4	34.4	44.7	141.0	79.4	66.8	79.4	110.0	141.0	355.0	110.0	106.0	110.0	240.0	355.0	141.0	89.1	79.4	79.4	141.0	141.0
038	31.6	22.4	11.9	11.9	31.6	31.6	141.0	63.5	59.6	63.5	141.0	141.0	355.0	150.0	141.0	150.0	240.0	355.0	224.0	141.0	141.0	141.0	224.0	224.0
039	89.1	33.5	22.4	42.2	42.2	42.2	140.0	63.5	106.0	110.0	141.0	141.0	237.0	80.0	130.0	150.0	178.0	237.0	282.0	66.8	106.0	155.0	240.0	240.0
040*	44.7	44.7	44.7	44.7	44.7	44.7	141.0	79.4	141.0	141.0	141.0	141.0	355.0	141.0	355.0	355.0	355.0	355.0	355.0	141.0	141.0	299.0	355.0	355.0
041*	10.0	4.2	4.2	4.2	10.0	10.0	44.7	22.4	22.4	34.4	44.7	44.7	79.4	35.5	35.5	66.8	66.8	79.4	79.4	35.5	35.5	66.8	79.4	79.4
042*	35.5	17.8	17.8	22.4	35.5	35.5	141.0	56.2	56.2	70.5	133.0	141.0	355.0	89.1	89.1	89.1	240.0	355.0	355.0	110.0	89.1	141.0	240.0	355.0
043*	31.6	17.8	17.8	22.4	31.6	31.6	141.0	70.5	70.5	110.0	141.0	141.0	355.0	89.1	89.1	224.0	282.0	335.0	355.0	89.1	89.1	224.0	282.0	355.0
044*	44.7	22.4	22.4	22.4	44.7	44.7	79.4	42.2	42.2	56.2	79.4	79.4	141.0	65.8	84.1	110.0	141.0	141.0	141.0	84.1	84.1	133.0	141.0	141.0
045	44.7	17.8	17.8	22.4	34.4	44.7	141.0	42.2	34.4	34.4	119.0	133.0	141.0	59.6	42.2	42.2	119.0	141.0	141.0	59.6	42.2	59.6	89.1	141.0
046*	79.4	17.8	17.8	34.4	44.7	66.8	141.0	56.2	42.2	89.1	141.0	141.0	355.0	66.8	56.2	178.0	355.0	355.0	355.0	66.8	66.8	178.0	355.0	355.0
047*	17.8	11.9	11.9	17.8	17.8	17.8	79.4	42.2	56.2	79.4	79.4	79.4	141.0	63.1	63.1	133.0	141.0	141.0	141.0	63.1	56.2	133.0	133.0	141.0

Table A7.3a (continued)

048*	17.8	10.0	17.8	17.8	17.8	17.8	119.0	79.4	79.4	119.0	119.0	119.0	150.0	119.0	119.0	141.0	141.0	150.0	141.0	119.0	119.0	141.0	141.0	141.0
049	70.8	66.8	84.1	70.8	70.8	70.8	22.4	178.0	224.0	178.0	224.0	224.0	398.0	355.0	316.0	251.0	355.0	398.0	355.0	355.0	316.0	299.0	355.0	355.0
050	22.4	8.4	10.0	17.8	22.4	22.4	79.4	31.6	33.4	70.9	79.4	79.4	112.0	63.1	63.1	79.4	112.0	112.0	141.0	70.9	70.9	79.4	112.0	141.0
051*	17.8	7.1	7.1	10.0	17.8	17.8	79.4	22.4	22.4	44.7	56.2	79.4	79.4	34.4	22.4	56.2	79.4	79.4	79.4	22.4	17.8	34.4	56.2	79.4
052	50.1	35.5	33.5	50.0	50.0	50.0	158.0	150.0	119.0	112.0	150.0	150.0	178.0	150.0	141.0	141.0	150.0	178.0	178.0	133.0	141.0	158.0	178.0	178.0

* Subject participated both Experiment 2 and Experiment 4.

Table A7.3b. Spreadsheet for Experiment 2 showing contrast sensitivity before and after LASIK.

Subjects	6.9 cpd						10.3 cpd						20.5 cpd					
	1st	2nd	3rd	4th	5th	6th	1st	2nd	3rd	4th	5th	6th	1st	2nd	3rd	4th	5th	6th
001*	31.6	10.0	10.0	14.1	22.4	31.6	14.1	4.0	4.0	7.0	10.0	10.0	2.0	1.0	2.0	2.0	2.0	2.2
002	200.0	282.0	168.0	237.0	240.0	240.0	35.5	75.0	59.6	79.4	75.0	75.0	1.6	10.6	7.1	10.6	10.6	7.1
003*	141.0	110.0	110.0	141.0	141.0	141.0	31.6	10.6	10.6	22.4	31.6	31.6	2.8	2.0	2.0	2.0	2.0	2.0
004	126.0	94.4	94.4	141.0	126.0	126.0	42.2	25.1	42.2	40.1	42.2	42.2	5.6	2.0	2.8	3.4	2.0	3.4
005*	141.0	119.0	106.0	119.0	133.0	133.0	47.3	37.6	35.5	37.6	35.5	37.6	2.0	2.1	2.0	2.0	2.0	2.0
006	70.9	56.2	44.7	56.2	70.9	70.9	23.7	17.8	17.8	17.8	23.7	23.7	2.0	2.2	2.0	2.0	2.0	2.2
008*	126.0	89.1	84.1	89.1	100.0	89.1	75.0	33.5	35.5	35.5	47.3	39.8	7.5	3.0	2.2	3.0	5.6	5.3
009*	355.0	237.0	251.0	355.0	355.0	355.0	141.0	79.4	79.4	79.4	79.4	141.0	31.6	17.8	17.8	23.7	12.6	23.7
011	89.1	84.1	106.0	106.0	106.0	84.1	37.6	33.4	44.7	37.6	37.6	37.6	6.0	4.0	6.0	5.4	5.4	7.1
012*	94.4	34.4	34.4	50.1	44.7	89.1	18.8	7.1	7.1	7.1	14.1	18.8	4.0	2.0	2.0	2.0	2.0	2.2
013	200.0	158.0	112.0	168.0	200.0	200.0	50.1	56.2	50.1	59.6	79.4	59.6	10.6	7.9	6.3	8.4	7.9	7.9
014	79.4	47.3	70.8	70.8	70.8	79.4	35.5	21.1	22.4	21.1	35.5	35.5	1.2	1.0	2.1	2.0	2.0	2.0
016	100.0	79.4	70.8	70.8	100.0	100.0	31.6	17.8	21.1	22.4	31.6	31.6	5.0	3.4	4.0	4.4	4.0	4.0
022*	282.0	112.0	112.0	100.0	237.0	237.0	75.0	33.5	44.7	42.2	28.2	66.8	7.9	6.0	8.4	5.3	3.5	7.4
025	112.0	66.8	79.4	79.4	112.0	112.0	31.6	34.4	33.5	33.5	33.5	31.6	4.4	4.0	5.6	4.0	5.6	4.0
027*	43.9	31.6	31.6	31.6	31.6	43.9	28.1	17.8	17.8	23.7	28.1	13.9	3.2	2.0	2.0	3.2	4.4	3.2
028	178.0	133.0	133.0	126.0	168.0	168.0	66.8	70.8	66.8	70.8	66.8	66.8	8.9	7.5	4.2	8.9	8.9	7.5
029	100.0	89.1	133.0	100.0	100.0	100.0	56.2	44.7	47.3	56.2	47.3	56.2	3.2	2.1	3.0	3.2	3.2	3.2
030*	56.2	22.4	44.7	39.8	44.7	56.2	12.6	6.3	8.4	12.6	12.6	12.6	1.0	1.0	1.0	2.0	1.0	1.0
031	100.0	50.1	50.1	56.2	75.0	100.0	22.4	10.6	10.6	31.6	25.1	22.4	1.0	1.0	1.0	1.0	1.0	1.0
032	200.0	112.0	178.0	266.0	200.0	200.0	70.8	59.6	75.0	112.0	75.0	70.8	14.1	10.6	10.6	15.0	10.6	10.6
033*	100.0	42.2	42.2	42.2	56.2	79.4	56.2	22.4	22.4	22.4	33.4	56.2	7.1	4.0	4.0	4.0	4.0	7.1
034*	37.6	31.6	37.6	37.6	37.6	37.6	26.6	20.0	17.8	20.0	20.0	26.6	4.0	5.0	4.0	4.0	4.0	4.0
035*	79.4	79.4	79.4	79.4	79.4	79.4	56.2	31.6	31.6	56.2	56.2	56.2	10.0	7.0	7.0	7.0	7.0	7.0
036*	44.7	52.1	31.6	31.6	31.6	44.7	17.8	5.6	5.6	10.0	10.0	17.8	17.8	1.0	1.0	1.0	1.0	1.0
037*	79.4	34.4	34.4	34.4	63.5	63.5	17.8	14.1	14.1	14.1	17.8	17.8	10.0	7.0	4.0	4.0	4.0	7.0
038	141.0	75.0	63.5	63.5	75.0	138.0	56.2	33.4	22.4	22.4	56.2	56.2	25.1	10.0	7.0	10.0	10.0	10.0
039	200.0	33.5	22.4	106.0	200.0	200.0	47.3	8.4	6.7	10.6	14.1	33.5	8.0	1.0	1.2	2.0	4.2	7.1
040*	141.0	79.4	79.4	79.4	141.0	141.0	79.4	64.4	17.8	34.4	31.6	44.7	17.8	10.0	10.0	10.0	10.0	17.8
041*	44.7	22.4	17.8	22.4	34.4	44.7	10.0	10.0	7.0	10.0	10.0	10.0	2.2	2.2	2.2	2.2	2.2	2.2
042*	200.0	42.2	34.4	110.0	200.0	200.0	56.2	22.4	22.4	56.2	56.2	56.2	10.0	4.0	4.0	7.0	7.0	10.0
043*	141.0	42.2	33.5	106.0	141.0	141.0	31.6	17.8	14.1	22.4	31.6	31.6	1.6	1.6	1.6	1.6	1.6	1.6
044*	141.0	65.8	79.4	110.0	141.0	141.0	44.7	22.4	22.4	31.6	31.6	31.6	10.0	4.0	4.0	5.6	5.6	7.1
045	79.4	22.4	22.4	22.4	34.4	59.6	31.6	8.9	7.0	7.0	14.1	22.4	4.0	1.0	1.0	1.0	1.0	1.0
046*	141.0	34.4	34.4	89.1	141.0	141.0	79.4	17.8	17.8	66.8	79.4	79.4	5.0	2.0	2.0	4.0	3.4	4.0

Table 7.3b (continued)

047*	44.7	22.4	22.4	44.7	44.7	44.7	17.8	10.6	11.9	17.8	17.8	17.8	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4
048*	119.0	79.4	79.4	119.0	119.0	119.0	44.7	28.8	31.6	31.6	44.7	44.7	7.1	5.6	5.6	7.1	11.9	22.4		
049	224.0	133.0	168.0	141.0	224.0	224.0	50.1	56.2	75.0	66.8	66.8	56.2	4.0	5.3	6.0	4.0	5.3	6.0		
050	112.0	70.9	70.9	79.4	112.0	112.0	79.4	31.6	33.4	70.9	79.4	79.4	17.8	4.0	4.0	7.1	7.1	17.8		
051*	17.8	7.1	10.0	10.0	14.1	14.1	10.0	2.0	2.0	2.0	4.0	7.1	1.0	1.0	1.0	1.0	1.0	1.0		
052	79.4	89.1	79.4	106.0	106.0	106.0	14.1	21.1	17.8	17.8	21.1	17.8	3.4	2.5	2.5	2.5	2.5	2.5		

* Subject participated both Experiment 2 and Experiment 4.

Table A7.3c. Spreadsheet for Experiment 2 showing contrast sensitivity before and after LASIK in ratio.

	0.3 cpd						0.8 cpd						1.5 cpd						3.4 cpd					
Subjects	1st	2nd	3rd	4th	5th	6th	1st	2nd	3rd	4th	5th	6th	1st	2nd	3rd	4th	5th	6th	1st	2nd	3rd	4th	5th	6th
001*	1.00	0.38	0.25	0.47	0.47	0.47	1.00	0.45	0.76	0.79	1.01	1.01	1.00	0.34	0.55	0.63	0.75	1.00	1.00	0.24	0.38	0.55	0.85	0.85
002	1.00	1.33	1.12	1.33	1.19	1.19	1.00	1.06	1.13	1.13	1.13	1.13	1.00	0.89	1.12	1.12	1.26	1.12	1.00	1.00	0.79	1.33	1.26	1.26
003*	1.00	1.78	1.78	1.41	1.19	1.19	1.00	0.79	0.79	0.89	0.94	0.94	1.00	0.84	1.06	1.12	1.06	1.00	1.00	0.63	0.75	0.94	0.94	0.94
004	1.00	1.19	0.85	0.80	1.00	1.00	1.00	0.89	0.89	1.00	1.12	1.00	1.00	0.79	0.42	0.45	0.67	0.79	1.00	0.67	0.60	0.45	1.00	0.79
005*	1.00	0.89	0.84	0.89	0.89	0.89	1.00	0.99	0.79	0.79	0.79	0.79	1.00	0.94	0.79	0.94	1.33	0.79	1.00	0.83	0.90	0.90	0.90	0.78
006	1.00	1.06	1.00	1.00	1.06	1.06	1.00	0.75	0.67	0.67	0.75	0.75	1.00	0.75	0.45	0.75	0.75	1.00	1.00	0.84	0.84	0.84	1.00	1.00
008*	1.00	0.71	0.67	1.00	1.00	1.00	1.00	0.95	0.75	0.71	0.95	0.95	1.00	0.84	0.79	0.79	0.84	1.00	1.00	0.75	0.79	0.89	1.00	1.00
009*	1.00	0.47	0.53	0.53	0.94	0.79	1.00	0.56	0.50	0.56	1.00	0.71	1.00	0.80	0.84	0.84	0.80	1.06	1.00	0.67	0.71	0.75	1.00	0.89
011	1.00	0.94	1.19	1.00	1.00	1.00	1.00	7.95	10.00	7.95	10.00	10.00	1.00	0.89	0.79	0.63	0.89	1.00	1.00	1.00	0.89	0.84	1.00	1.00
012*	1.00	0.95	0.95	0.95	0.75	0.95	1.00	0.71	0.80	0.71	0.60	0.89	1.00	0.75	0.84	1.00	1.00	1.00	1.00	0.63	0.84	1.00	1.06	1.00
013	1.00	0.67	0.67	0.75	0.75	0.94	1.00	0.53	0.53	0.56	0.56	0.89	1.00	0.35	0.35	0.45	0.56	1.00	1.00	0.33	0.33	0.53	0.60	0.94
014	1.00	0.84	0.80	0.94	1.00	1.00	1.00	0.79	0.94	0.94	1.19	1.00	1.00	1.19	1.78	1.58	1.78	1.19	1.00	0.75	0.84	0.84	0.67	1.00
016	1.00	0.56	0.94	0.94	0.94	0.94	1.00	0.79	1.00	0.79	1.00	1.00	1.00	0.67	0.71	0.71	0.79	1.00	1.00	0.63	0.75	0.75	1.00	1.00
022*	1.00	0.60	0.45	0.63	1.00	1.00	1.00	0.50	0.36	0.40	1.00	1.00	1.00	0.71	0.50	0.45	0.50	0.89	1.00	0.71	0.63	0.89	0.89	0.94
025	1.00	0.89	0.89	0.89	0.71	0.89	1.00	0.84	0.89	0.94	0.79	0.84	1.00	0.56	0.63	0.60	0.56	0.94	1.00	0.56	0.79	0.94	0.94	1.00
027*	1.00	0.71	0.75	0.75	1.00	1.00	1.00	0.68	0.68	0.68	1.00	1.00	1.00	0.84	0.89	0.89	0.89	1.00	1.00	0.68	0.64	0.68	1.00	1.00
028	1.00	0.66	0.66	1.00	1.00	1.00	1.00	0.56	0.56	0.66	0.89	1.00	1.00	0.63	0.63	0.63	0.63	0.88	1.00	0.40	0.72	0.81	0.81	0.72
029	1.00	0.51	1.00	1.00	1.00	1.00	1.00	0.89	0.94	1.26	1.00	1.00	1.00	0.91	0.91	1.01	1.00	1.00	1.00	0.79	0.94	0.89	1.26	1.26
030*	1.00	0.40	0.60	1.00	1.00	1.00	1.00	0.75	0.89	1.00	1.00	1.00	1.00	0.79	0.94	1.00	0.94	1.00	1.00	0.63	0.95	1.00	1.00	1.00
031	1.00	0.71	1.09	1.26	1.09	1.09	1.00	0.63	0.60	0.71	1.00	1.00	1.00	0.53	0.56	0.56	0.71	0.94	1.00	0.71	0.94	1.00	0.94	0.94
032	1.00	0.40	0.40	0.40	0.89	0.89	1.00	0.50	0.84	1.00	1.00	1.00	1.00	0.47	0.67	0.71	0.89	1.00	1.00	0.79	0.71	0.71	0.79	1.00
033*	1.00	0.63	0.63	1.00	1.00	1.00	1.00	0.60	0.43	0.60	1.00	1.00	1.00	0.42	0.56	0.71	1.00	1.00	1.00	0.56	0.62	0.80	0.96	0.96
034*	1.00	0.79	0.79	0.79	1.00	1.00	1.00	0.84	0.60	0.60	0.84	1.00	1.00	0.42	0.33	0.33	0.56	0.71	1.00	0.56	0.42	0.56	0.79	1.00
035*	1.00	0.89	0.89	0.86	1.00	1.00	1.00	0.89	0.89	1.00	1.00	1.01	1.00	0.70	0.75	0.75	0.75	1.00	1.00	0.70	0.75	0.75	1.00	1.00
036*	1.00	0.80	1.00	0.89	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.67	1.00	1.00	1.00	1.00	1.00	0.67	0.79	0.79	0.79	1.00
037*	1.00	0.79	0.79	0.79	1.00	1.00	1.00	0.69	0.89	0.89	1.12	1.12	1.00	0.79	1.00	1.00	1.00	1.00	1.00	0.71	0.79	0.79	1.00	1.00
038	1.00	0.50	0.50	0.50	0.77	1.00	1.00	0.56	0.47	0.56	0.78	1.00	1.00	0.31	0.30	0.31	0.68	1.00	1.00	0.63	0.56	0.56	1.00	1.00
039	1.00	0.71	0.38	0.38	1.00	1.00	1.00	0.45	0.42	0.45	1.00	1.00	1.00	0.42	0.40	0.42	0.68	1.00	1.00	0.63	0.63	0.63	1.00	1.00
040*	1.00	0.45	0.45	0.71	1.00	1.00	1.00	0.50	0.50	0.71	1.00	1.00	1.00	0.40	0.40	0.56	0.80	0.80	1.00	0.40	0.40	0.56	0.80	1.00
041*	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.56	1.00	1.00	1.00	1.00	1.00	0.40	1.00	1.00	1.00	1.00	1.00	0.40	0.40	0.84	1.00	1.00
042*	1.00	0.42	0.42	0.42	1.00	1.00	1.00	0.50	0.50	0.77	1.00	1.00	1.00	0.45	0.45	0.84	0.84	1.00	1.00	0.45	0.45	0.84	1.00	1.00
043*	1.00	0.40	0.40	0.56	1.00	1.00	1.00	0.28	0.28	0.56	0.71	1.00	1.00	0.43	0.28	0.71	1.00	1.00	1.00	0.28	0.22	0.43	0.71	1.00
044*	1.00	0.56	0.56	0.71	1.00	1.00	1.00	0.50	0.50	0.78	1.00	1.00	1.00	0.25	0.25	0.63	0.79	0.94	1.00	0.25	0.25	0.63	0.79	1.00
045	1.00	0.50	0.50	0.50	1.00	1.00	1.00	0.53	0.53	0.71	1.00	1.00	1.00	0.47	0.60	0.78	1.00	1.00	1.00	0.60	0.60	0.94	1.00	1.00
046*	1.00	0.22	0.22	0.43	0.56	0.84	1.00	0.40	0.30	0.63	1.00	1.00	1.00	0.19	0.16	0.50	1.00	1.00	1.00	0.19	0.19	0.50	1.00	1.00
047*	1.00	0.40	0.40	0.50	0.77	1.00	1.00	0.30	0.24	0.24	0.84	0.94	1.00	0.42	0.30	0.30	0.84	1.00	1.00	0.42	0.30	0.42	0.63	1.00

Table A7.3c (continued)

048*	1.00	0.67	0.67	1.00	1.00	1.00	1.00	0.53	0.71	1.00	1.00	1.00	1.00	0.45	0.45	0.94	1.00	1.00	1.00	0.45	0.40	0.94	0.94	1.00
049	1.00	0.56	1.00	1.00	1.00	1.00	1.00	0.67	0.67	1.00	1.00	1.00	1.00	0.79	0.79	0.94	0.94	1.00	1.00	0.84	0.84	1.00	1.00	1.00
050	1.00	0.50	0.50	0.63	1.00	1.00	1.00	0.40	0.40	0.50	0.94	1.00	1.00	0.25	0.25	0.25	0.68	1.00	1.00	0.31	0.25	0.40	0.68	1.00
051*	1.00	0.38	0.45	0.79	1.00	1.00	1.00	0.40	0.42	0.89	1.00	1.00	1.00	0.56	0.56	0.71	1.00	1.00	1.00	0.50	0.50	0.56	0.79	1.00
052	1.00	0.63	0.63	0.80	1.00	1.00	1.00	0.67	0.84	0.84	1.00	1.00	1.00	0.71	0.71	1.00	1.00	1.00	1.00	0.71	0.71	1.00	1.00	1.00

* Subject participated both Experiment 2 and Experiment 4.

Table A7.3d. Spreadsheet for Experiment 2 showing contrast sensitivity before and after LASIK in ratio.

Subjects	6.9 cpd						10.3 cpd						20.5 cpd					
	1st	2nd	3rd	4th	5th	6th	1st	2nd	3rd	4th	5th	6th	1st	2nd	3rd	4th	5th	6th
001*	1.00	0.17	0.11	0.53	1.00	1.00	1.00	0.18	0.14	0.22	0.30	0.71	1.00	0.13	0.15	0.25	0.53	0.89
002	1.00	1.41	0.84	1.19	1.20	1.20	1.00	2.11	1.68	2.24	2.11	2.11	1.00	6.63	4.44	6.63	6.63	4.44
003*	1.00	0.56	0.89	1.33	1.00	1.00	1.00	0.84	1.06	1.58	1.06	1.00	1.00	0.75	0.75	1.06	0.75	0.75
004	1.00	0.75	0.75	0.71	0.94	0.94	1.00	1.06	1.00	1.06	1.00	1.00	1.00	0.84	0.47	1.00	1.00	0.84
005*	1.00	0.84	0.75	0.84	0.94	0.94	1.00	0.79	0.75	0.79	0.75	0.79	1.00	1.05	1.00	1.00	1.00	1.00
006	1.00	0.79	0.63	0.79	1.00	1.00	1.00	0.75	0.75	0.75	1.00	1.00	1.00	1.10	1.00	1.00	1.00	1.10
008*	1.00	1.12	1.00	1.34	1.34	1.34	1.00	1.50	1.26	1.26	1.50	1.26	1.00	0.74	0.74	0.74	0.74	0.74
009*	1.00	0.71	0.67	0.71	0.79	0.71	1.00	0.45	0.47	0.47	0.63	0.53	1.00	0.40	0.29	0.40	0.75	0.71
011	1.00	0.59	0.75	0.63	1.00	1.00	1.00	1.12	1.50	1.33	1.33	1.12	1.00	1.33	1.50	1.00	1.33	1.50
012*	1.00	0.94	1.19	1.19	1.19	0.94	1.00	0.89	1.19	1.00	1.00	1.00	1.00	0.67	1.00	0.90	0.90	1.18
013	1.00	0.36	0.36	0.53	0.47	0.94	1.00	0.38	0.38	0.38	0.75	1.00	1.00	0.50	0.50	0.50	0.50	0.55
014	1.00	0.79	0.56	0.84	1.00	1.00	1.00	1.12	1.00	1.19	1.58	1.19	1.00	0.75	0.59	0.79	0.75	0.75
016	1.00	0.60	0.89	0.89	0.89	1.00	1.00	0.59	0.63	0.59	1.00	1.00	1.00	0.83	1.75	1.67	1.67	1.67
022*	1.00	0.75	0.75	1.12	1.00	1.00	1.00	0.59	1.00	0.95	1.00	1.00	1.00	0.36	0.50	0.61	0.36	0.61
025	1.00	0.40	0.40	0.35	0.84	0.84	1.00	0.45	0.60	0.56	0.38	0.89	1.00	0.76	1.06	0.67	0.44	0.94
027*	1.00	0.60	0.71	0.71	1.00	1.00	1.00	1.09	1.06	1.06	1.06	1.00	1.00	0.91	1.27	0.91	1.27	0.91
028	1.00	0.72	0.72	0.72	0.72	1.00	1.00	0.63	0.63	0.84	1.00	0.49	1.00	0.63	0.63	1.00	1.38	1.00
029	1.00	0.79	0.71	0.71	1.00	1.00	1.00	0.56	0.67	0.71	1.00	1.00	1.00	0.68	0.80	0.88	0.80	0.80
030*	1.00	0.89	1.33	1.00	1.00	1.00	1.00	0.80	0.84	1.00	0.84	1.00	1.00	0.66	0.94	1.00	1.00	1.00
031	1.00	0.40	0.80	0.71	0.80	1.00	1.00	0.50	0.67	1.00	1.00	1.00	1.00	1.00	1.00	2.00	1.00	1.00
032	1.00	0.50	0.50	0.56	0.75	1.00	1.00	0.47	0.47	1.41	1.12	1.00	1.00	1.00	1.00	1.00	1.00	1.00
033*	1.00	0.78	0.78	1.00	1.00	1.00	1.00	0.34	0.34	0.71	1.00	1.00	1.00	0.71	0.71	0.71	0.71	0.71
034*	1.00	0.42	0.42	0.42	0.56	0.79	1.00	0.40	0.40	0.40	0.59	1.00	1.00	0.56	0.56	0.56	0.56	1.00
035*	1.00	0.84	1.00	1.00	1.00	1.00	1.00	0.75	0.67	0.75	0.75	1.00	1.00	1.25	1.00	1.00	1.00	1.00
036*	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.56	0.56	1.00	1.00	1.00	1.00	0.70	0.70	0.70	0.70	0.70
037*	1.00	1.17	0.71	0.71	0.71	1.00	1.00	0.31	0.31	0.56	0.56	1.00	1.00	0.06	0.06	0.06	0.06	0.06
038	1.00	0.43	0.43	0.43	0.80	0.80	1.00	0.79	0.79	0.79	1.00	1.00	1.00	0.70	0.40	0.40	0.40	0.70
039	1.00	0.53	0.45	0.45	0.53	0.98	1.00	0.59	0.40	0.40	1.00	1.00	1.00	0.40	0.28	0.40	0.40	0.40
040*	1.00	0.32	0.32	0.45	0.71	1.00	1.00	0.28	0.28	0.50	0.71	0.71	1.00	0.50	1.00	1.00	1.00	1.10
041*	1.00	0.56	0.56	0.56	1.00	1.00	1.00	0.81	0.22	0.43	0.40	0.56	1.00	0.56	0.56	0.56	0.56	1.00
042*	1.00	0.50	0.40	0.50	0.77	1.00	1.00	1.00	0.70	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
043*	1.00	0.40	0.56	0.56	0.79	0.79	1.00	0.20	0.20	0.20	0.40	0.71	1.00	1.00	1.00	1.00	1.00	1.00
044*	1.00	0.30	0.24	0.75	1.00	1.00	1.00	0.56	0.45	0.71	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
045	1.00	0.47	0.56	0.78	1.00	1.00	1.00	0.50	0.50	0.71	0.71	0.71	1.00	0.40	0.40	0.56	0.56	0.71
046*	1.00	0.24	0.24	0.63	1.00	1.00	1.00	0.22	0.22	0.84	1.00	1.00	1.00	0.40	0.40	0.80	0.68	0.80

Table 7.3d (continued)

047*	1.00	0.28	0.28	0.28	0.43	0.75	1.00	0.28	0.22	0.22	0.45	0.71	1.00	0.25	0.25	0.25	0.25	0.25
048*	1.00	0.50	0.50	1.00	1.00	1.00	1.00	0.60	0.67	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
049	1.00	0.67	0.67	1.00	1.00	1.00	1.00	0.64	0.71	0.71	1.00	1.00	1.00	0.79	0.79	1.00	1.68	3.15
050	1.00	0.21	0.17	0.55	1.00	1.00	1.00	0.40	0.40	1.00	1.00	1.00	1.00	0.40	0.40	0.70	0.70	1.00
051*	1.00	0.63	0.63	0.71	1.00	1.00	1.00	0.40	0.42	0.89	1.00	1.00	1.00	0.22	0.22	0.40	0.40	1.00
052	1.00	0.67	0.71	1.00	1.00	1.00	1.00	0.56	0.56	0.56	0.56	1.00	1.00	0.56	0.56	0.75	0.40	0.75

* Subject participated both Experiment 2 and Experiment 4.

Table A7.4a. Spreadsheet for Experiment 4 showing the reduction in contrast sensitivity with and without glare before and after LASIK.

	0.3 cpd						0.8 cpd						1.5 cpd						3.4 cpd					
Subjects	1st	2nd	3rd	4th	5th	6th	1st	2nd	3rd	4th	5th	6th	1st	2nd	3rd	4th	5th	6th	1st	2nd	3rd	4th	5th	6th
001	29.2	27.1	25.1	27.1	27.1	23.6	61.4	73.3	53.9	41.5	41.5	35.2	90.4	87.9	96.6	87.9	73.4	52.2	212.0	185.0	188.0	188.0	188.0	174.0
003	3.6	9.1	11.1	7.2	5.0	8.8	39.2	35.9	29.4	37.2	39.2	30.3	32.0	36.9	76.6	33.0	26.0	35.0	32.0	27.0	35.0	24.0	32.0	31.0
005	37.3	43.9	32.9	32.4	32.4	33.3	63.6	62.1	62.1	54.7	44.8	51.9	138.0	89.6	89.6	96.7	88.9	138.0	111.0	99.7	99.7	107.0	88.0	92.0
008	26.6	18.8	18.8	26.6	21.6	21.6	43.8	46.2	46.2	45.0	44.4	34.2	58.0	56.1	65.6	43.8	43.8	44.9	39.0	33.8	53.0	46.2	41.2	43.8
009	13.8	16.1	16.6	22.0	16.6	16.6	51.9	66.7	49.7	55.3	51.9	51.9	73.0	88.3	84.8	61.6	78.0	96.0	73.0	133.0	137.0	104.0	96.0	96.0
012	17.5	18.0	16.6	23.8	17.5	9.2	21.8	25.7	16.6	18.8	24.6	24.6	36.9	24.4	44.4	53.0	52.5	43.8	187.9	123.0	137.2	182.2	184.0	184.0
022	2.4	14.4	14.4	6.2	4.6	4.6	4.3	25.6	15.9	12.1	21.8	17.4	-12.0	34.4	25.6	15.6	22.8	23.0	10.9	52.8	27.8	38.4	37.2	29.2
027	36.6	32.0	32.0	30.4	36.1	36.1	30.1	33.5	33.5	30.1	30.1	30.1	44.3	45.8	48.4	35.5	36.4	33.6	44.3	45.8	36.4	35.5	49.7	49.7
030	13.9	10.0	15.1	12.4	15.1	15.1	43.9	54.3	47.8	47.8	47.8	47.8	51.9	62.8	61.6	51.9	51.9	51.9	51.9	62.8	55.8	55.8	55.8	51.9
033	16.1	15.8	12.2	11.5	16.1	16.1	30.1	24.4	34.7	26.9	21.8	21.8	51.2	49.0	65.3	45.0	45.0	45.0	34.7	42.1	40.7	40.7	45.0	45.0
034	22.3	20.4	19.0	19.0	23.2	22.3	77.9	76.0	63.4	71.6	75.6	74.2	243.0	106.6	98.2	102.2	205.6	243.0	77.9	81.3	71.6	76.0	70.2	70.2
035	27.1	10.4	10.4	17.9	13.8	13.8	38.4	17.9	17.9	27.9	33.9	33.9	71.2	26.0	27.6	40.2	56.1	52.7	45.0	27.1	27.6	39.1	51.6	45.0
036	24.7	34.7	26.9	26.9	26.9	26.9	61.6	59.4	77.9	61.6	61.6	61.6	73.0	81.4	131.0	73.0	73.0	73.0	73.0	81.4	81.4	75.0	73.0	73.0
037	5.5	2.2	2.2	2.2	2.2	5.5	24.7	18.4	18.4	27.0	26.9	26.9	59.4	31.5	31.5	56.5	46.8	61.6	45.0	31.5	31.5	49.0	46.8	61.6
040	-2.2	3.7	3.7	7.6	7.6	7.6	51.2	19.0	19.0	41.3	33.8	34.7	51.2	31.0	19.0	52.8	57.0	45.0	34.4	20.4	15.8	32.0	33.8	34.4
041	9.2	14.4	14.4	14.6	17.2	17.2	29.0	62.7	62.7	87.6	70.5	70.5	155.0	74.7	71.3	189.6	247.6	138.0	77.0	81.3	81.3	112.0	104.0	111.0
042	16.5	15.0	15.0	15.0	10.3	10.3	16.3	34.8	34.8	45.9	54.7	27.5	29.0	58.4	79.7	99.7	96.3	89.1	61.6	78.5	80.4	92.3	89.1	89.1
043	12.6	10.4	10.4	24.1	22.3	22.1	62.2	45.9	34.8	76.5	74.2	74.2	243.0	54.2	48.8	165.4	243.0	243.0	77.0	56.5	59.4	66.0	77.0	77.0
044	-2.2	8.5	8.5	14.4	14.4	14.4	16.3	34.4	48.4	76.0	76.0	71.6	77.9	55.3	55.3	76.8	77.9	77.9	77.9	59.7	48.4	76.8	88.3	70.2
046	3.7	2.9	3.7	3.7	3.7	3.7	55.9	57.0	57.0	55.9	55.9	55.9	60.9	83.5	91.2	51.9	51.9	60.9	51.9	62.8	74.3	51.9	51.9	51.9
047	13.1	14.4	14.4	19.0	20.8	20.8	105.5	48.4	48.4	62.7	97.5	84.8	77.0	81.3	81.3	74.4	93.0	99.0	77.0	95.3	77.5	96.3	93.0	77.0
048	4.6	4.4	6.0	13.3	17.9	17.9	43.9	21.6	19.3	48.5	57.0	57.0	32.6	45.3	40.7	34.7	32.6	32.6	51.9	39.3	56.8	34.7	67.3	61.6
051	20.7	25.5	25.5	22.3	20.7	20.7	39.6	43.9	43.8	36.9	39.6	39.6	197.0	172.0	172.0	177.0	177.0	177.0	177.0	195.0	188.0	177.0	177.0	177.0

Table A7.4b. Spreadsheet for Experiment 4 showing the reduction in contrast sensitivity with and without glare before and after LASIK.

Subjects	6.9 cpd						10.3 cpd						20.5 cpd					
	1st	2nd	3rd	4th	5th	6th	1st	2nd	3rd	4th	5th	6th	1st	2nd	3rd	4th	5th	6th
001	133.0	108.0	95.4	108.0	122.0	121.0	44.1	34.1	32.0	34.1	32.0	32.9	.9	1.1	1.0	1.0	.9	.0
003	20.0	29.5	24.5	29.5	25.0	14.1	8.2	9.8	8.9	8.9	13.8	8.2	.8	.0	-.8	.8	1.6	-.3
005	52.2	29.8	29.8	29.4	22.1	44.4	-3.6	1.1	2.5	3.4	9.5	-3.6	.6	.0	1.0	.0	.0	.2
008	12.3	13.8	13.8	13.8	13.8	12.3	18.1	15.8	15.8	15.9	16.9	10.7	.0	.0	.0	.8	1.0	1.0
009	21.8	20.0	22.3	22.0	22.3	21.8	6.3	5.3	6.4	4.8	6.3	6.3	.0	.0	.0	.9	1.0	.8
012	77.9	92.2	95.3	98.8	98.8	98.8	9.2	7.2	8.6	11.2	9.2	13.8	1.8	1.0	1.0	1.0	1.0	1.0
022	-12.0	40.2	34.4	38.8	52.0	57.0	21.8	21.4	20.4	20.4	22.2	21.8	1.7	3.0	2.6	2.6	1.6	.8
027	6.0	20.4	19.8	11.0	11.0	19.8	15.4	13.7	11.5	8.8	8.8	12.2	.6	4.0	.6	.6	1.6	.6
030	59.4	57.0	47.8	57.0	57.0	57.0	21.8	24.6	24.6	21.8	24.6	24.6	7.5	5.6	5.6	5.6	5.6	5.6
033	16.5	15.1	13.8	13.8	13.8	16.9	6.6	4.6	8.0	7.8	6.6	10.0	.0	.0	.0	.0	.0	.0
034	43.9	31.0	31.0	31.0	39.1	41.1	10.0	12.1	12.1	12.1	15.8	10.0	5.5	6.0	3.0	3.0	3.0	5.0
035	27.1	4.4	6.3	12.1	17.9	20.4	2.9	3.0	2.0	5.0	6.6	6.6	1.0	.0	1.0	1.0	1.0	1.2
036	41.0	43.9	43.9	34.7	41.0	41.0	16.3	12.0	15.8	16.6	13.8	16.9	9.9	7.8	8.0	5.3	8.0	6.0
037	24.7	20.4	15.8	20.4	22.8	30.0	5.5	9.0	5.0	8.0	5.5	8.0	1.2	1.2	1.2	1.2	1.2	1.2
040	3.7	5.9	8.8	8.8	6.3	6.3	2.9	1.0	1.0	1.0	2.0	3.7	.0	.0	.0	.0	.0	.0
041	29.0	31.0	25.7	35.5	29.0	29.0	17.5	15.8	12.1	14.6	13.8	13.8	-.9	.6	.6	.6	.6	.6
042	75.2	62.1	77.4	75.6	84.8	75.2	20.6	21.4	21.4	26.9	29.6	29.6	2.1	3.0	3.0	4.6	4.6	6.1
043	29.0	24.1	27.0	22.3	29.0	29.0	12.6	15.8	15.8	10.6	12.6	12.6	2.8	1.0	1.0	3.0	2.4	3.0
044	26.9	20.4	20.4	26.9	26.9	22.3	3.7	9.6	9.9	15.8	15.8	15.8	.0	.4	.4	.4	.4	.4
046	55.9	57.0	50.6	55.9	55.9	55.9	9.2	18.8	11.6	11.6	24.7	24.7	4.6	4.6	4.6	4.6	4.6	4.6
047	22.0	22.4	23.2	39.3	22.0	22.0	21.8	20.4	20.4	21.8	21.8	33.8	7.5	3.0	3.0	6.0	6.0	9.0
048	61.9	60.9	60.9	57.0	61.9	61.9	34.7	27.6	29.4	36.5	34.7	34.7	3.1	3.0	3.0	3.1	3.1	3.1
051	243.0	227.0	229.0	243.0	241.0	241.0	70.2	75.4	76.0	71.6	75.4	70.2	13.8	15.8	16.8	22.7	11.4	9.0

Table A7.4c. Spreadsheet for Experiment 4 showing the reduction in contrast sensitivity with and without glare before and after LASIK in ratio.

Subjects	0.3 cpd						0.8 cpd						1.5 cpd						3.4 cpd					
	1st	2nd	3rd	4th	5th	6th	1st	2nd	3rd	4th	5th	6th	1st	2nd	3rd	4th	5th	6th	1st	2nd	3rd	4th	5th	6th
001	1	0.9281	0.8596	0.9281	0.9281	0.8082	1	1.1938	0.8779	0.6759	0.6759	0.5733	1	0.9723	1.0686	0.9723	0.8119	0.5774	1	0.8726	0.8868	0.8868	0.8868	0.8208
003	1	2.5278	3.0833	2	1.3889	2.4444	1	0.9158	0.75	0.949	1	0.773	1	1.1531	2.3938	1.0313	0.8125	1.0938	1	0.8438	1.0938	0.75	1	0.9688
005	1	1.1769	0.882	0.8686	0.8686	0.8928	1	0.9764	0.9764	0.8601	0.7044	0.816	1	0.6493	0.6493	0.7007	0.6442	1	1	0.8982	0.8982	0.964	0.7928	0.8288
008	1	0.7068	0.7068	1	0.812	0.812	1	1.0548	1.0548	1.0274	1.0137	0.7808	1	0.9672	1.131	0.7552	0.7552	0.7741	1	0.8667	1.359	1.1846	1.0564	1.1231
009	1	1.1667	1.2029	1.5942	1.2029	1.2029	1	1.2852	0.9576	1.0655	1	1	1	1.2096	1.1616	0.8438	1.0685	1.3151	1	1.8219	1.8767	1.4247	1.3151	1.3151
012	1	1.0286	0.9486	1.36	1	0.5257	1	1.1789	0.7615	0.8624	1.1284	1.1284	1	0.6612	1.2033	1.4363	1.4228	1.187	1	0.6546	0.7302	0.9697	0.9792	0.9792
022	1	6	6	2.5833	1.9167	1.9167	1	5.9535	3.6977	2.814	5.0698	4.0465	1	-2.867	-2.133	-1.3	-1.9	-1.917	1	4.844	2.5505	3.5229	3.4128	2.6789
027	1	0.8743	0.8743	0.8306	0.9863	0.9863	1	1.113	1.113	1	1	1	1	1.0339	1.0926	0.8014	0.8217	0.7585	1	1.0339	0.8217	0.8014	1.1219	1.1219
030	1	0.7194	1.0863	0.8921	1.0863	1.0863	1	1.2369	1.0888	1.0888	1.0888	1.0888	1	1.21	1.1869	1	1	1	1	1.21	1.0751	1.0751	1.0751	1
033	1	0.9814	0.7578	0.7143	1	1	1	0.8106	1.1528	0.8937	0.7243	0.7243	1	0.957	1.2754	0.8789	0.8789	0.8789	1	1.2133	1.1729	1.1729	1.2968	1.2968
034	1	0.9148	0.852	0.852	1.0404	1	1	0.9756	0.8139	0.9191	0.9705	0.9525	1	0.4387	0.4041	0.4206	0.8461	1	1	1.0436	0.9191	0.9756	0.9012	0.9012
035	1	0.3838	0.3838	0.6605	0.5092	0.5092	1	0.4661	0.4661	0.7266	0.8828	0.8828	1	0.3652	0.3876	0.5646	0.7879	0.7402	1	0.6022	0.6133	0.8689	1.1467	1
036	1	1.4049	1.0891	1.0891	1.0891	1.0891	1	0.9643	1.2646	1	1	1	1	1.1151	1.7945	1	1	1	1	1.1151	1.1151	1.0274	1	1
037	1	0.4	0.4	0.4	0.4	1	1	0.7449	0.7449	1.0931	1.0891	1.0891	1	0.5303	0.5303	0.9512	0.7879	1.037	1	0.7	0.7	1.0889	1.04	1.3689
040	1	-1.682	-1.682	-3.455	-3.455	-3.455	1	0.3711	0.3711	0.8066	0.6602	0.6777	1	0.6055	0.3711	1.0313	1.1133	0.8789	1	0.593	0.4593	0.9302	0.9826	1
041	1	1.5652	1.5652	1.587	1.8696	1.8696	1	2.1621	2.1621	3.0207	2.431	2.431	1	0.4819	0.46	1.2232	1.5974	0.8903	1	1.0558	1.0558	1.4545	1.3506	1.4416
042	1	0.9091	0.9091	0.9091	0.6242	0.6242	1	2.135	2.135	2.816	3.3558	1.6871	1	2.0138	2.7483	3.4379	3.3207	3.0724	1	1.2744	1.3052	1.4984	1.4464	1.4464
043	1	0.8254	0.8254	1.9127	1.7698	1.754	1	0.7379	0.5595	1.2299	1.1929	1.1929	1	0.223	0.2008	0.6807	1	1	1	0.7338	0.7714	0.8571	1	1
044	1	-3.864	-3.864	-6.545	-6.545	-6.545	1	2.1104	2.9693	4.6626	4.6626	4.3926	1	0.7099	0.7099	0.9859	1	1	1	0.7664	0.6213	0.9859	1.1335	0.9012
046	1	0.7838	1	1	1	1	1	1.0197	1.0197	1	1	1	1	1.3711	1.4975	0.8522	0.8522	1	1	1.21	1.4316	1	1	1
047	1	1.0992	1.0992	1.4504	1.5878	1.5878	1	0.4588	0.4588	0.5943	0.9242	0.8038	1	1.0558	1.0558	0.9662	1.2078	1.2857	1	1.2377	1.0065	1.2506	1.2078	1
048	1	0.9565	1.3043	2.8913	3.8913	3.8913	1	0.492	0.4396	1.1048	1.2984	1.2984	1	1.3896	1.2485	1.0644	1	1	1	0.7572	1.0944	0.6686	1.2967	1.1869
051	1	1.2319	1.2319	1.0773	1	1	1	1.1086	1.1061	0.9318	1	1	1	0.8731	0.8731	0.8985	0.8985	0.8985	1	1.1017	1.0621	1	1	1

Table A7.4d. Spreadsheet for Experiment 4 showing the reduction in contrast sensitivity with and without glare before and after LASIK in ratio.

Subjects	6.9 cpd						10.3 cpd						20.5 cpd					
	1st	2nd	3rd	4th	5th	6th	1st	2nd	3rd	4th	5th	6th	1st	2nd	3rd	4th	5th	6th
001	1	0.812	0.7173	0.812	0.9173	0.9098	1	0.7732	0.7256	0.7732	0.7256	0.746	1	1.2222	1.1111	1.1111	1	0
003	1	1.475	1.225	1.475	1.25	0.705	1	1.1951	1.0854	1.0854	1.6829	1	1	0	-1	1	2	-0.375
005	1	0.5709	0.5709	0.5632	0.4234	0.8506	1	-0.306	-0.694	-0.944	-2.639	1	1	0	1.6667	0	0	0.3333
008	1	1.122	1.122	1.122	1.122	1	1	0.8729	0.8729	0.8785	0.9337	0.5912						
009	1	0.9174	1.0229	1.0092	1.0229	1	1	0.8413	1.0159	0.7619	1	1						
012	1	1.1836	1.2234	1.2683	1.2683	1.2683	1	0.7826	0.9348	1.2174	1	1.5	1	0.5556	0.5556	0.5556	0.5556	0.5556
022	1	-3.35	-2.867	-3.233	-4.333	-4.75	1	0.9817	0.9358	0.9358	1.0183	1	1	1.7647	1.5294	1.5294	0.9412	0.4706
027	1	3.4	3.3	1.8333	1.8333	3.3	1	0.8896	0.7468	0.5714	0.5714	0.7922	1	6.6667	1	1	2.6667	1
030	1	0.9596	0.8047	0.9596	0.9596	0.9596	1	1.1284	1.1284	1	1.1284	1.1284	1	0.7467	0.7467	0.7467	0.7467	0.7467
033	1	0.9152	0.8364	0.8364	0.8364	1.0242	1	0.697	1.2121	1.1818	1	1.5152						
034	1	0.7062	0.7062	0.7062	0.8907	0.9362	1	1.21	1.21	1.21	1.58	1	1	1.0909	0.5455	0.5455	0.5455	0.9091
035	1	0.1624	0.2325	0.4465	0.6605	0.7528	1	1.0345	0.6897	1.7241	2.2759	2.2759	1	0	1	1	1	1.2
036	1	1.0707	1.0707	0.8463	1	1	1	0.7362	0.9693	1.0184	0.8466	1.0368	1	0.7879	0.8081	0.5354	0.8081	0.6061
037	1	0.8259	0.6397	0.8259	0.9231	1.2146	1	1.6364	0.9091	1.4545	1	1.4545	1	1	1	1	1	1
040	1	1.5946	2.3784	2.3784	1.7027	1.7027	1	0.3448	0.3448	0.3448	0.6897	1.2759						
041	1	1.069	0.8862	1.2241	1	1	1	0.9029	0.6914	0.8343	0.7886	0.7886	1	-0.667	-0.667	-0.667	-0.667	-0.667
042	1	0.8258	1.0293	1.0053	1.1277	1	1	1.0388	1.0388	1.3058	1.4369	1.4369	1	1.4286	1.4286	2.1905	2.1905	2.9048
043	1	0.831	0.931	0.769	1	1	1	1.254	1.254	0.8413	1	1	1	0.3571	0.3571	1.0714	0.8571	1.0714
044	1	0.7584	0.7584	1	1	0.829	1	2.5946	2.6757	4.2703	4.2703	4.2703						
046	1	1.0197	0.9052	1	1	1	1	2.0435	1.2609	1.2609	2.6848	2.6848	1	1	1	1	1	1
047	1	1.0182	1.0545	1.7864	1	1	1	0.9358	0.9358	1	1	1.5505	1	0.4	0.4	0.8	0.8	1.2
048	1	0.9838	0.9838	0.9208	1	1	1	0.7954	0.8473	1.0519	1	1	1	0.9677	0.9677	1	1	1
051	1	0.9342	0.9424	1	0.9918	0.9918	1	1.0741	1.0826	1.0199	1.0741	1	1	1.1449	1.2174	1.6449	0.8261	0.6522

Table A7.5. Spreadsheet for Experiment 6 showing gender, age, preoperative refractive error and preoperative visual acuity of the subjects.

Subject	Gender	Age	Preoperative refractive error (D)	Preoperative visual acuity (logMAR)
1	M	36	-6.00/-0.25x170	0
2	F	41	-2.25/-1.00x175	0.02
3	F	34	-4.75/-0.25x160	0
4	M	32	-7.25-1.75x025	0
5	M	44	-6.50/-0.75x025	0
6	F	29	-4.75/-2.00x180	0.02
7	M	27	-4.75/-0.25x050	0
8	M	33	-6.00	0
9	M	41	-4.75/-0.50x075	0
10	M	42	-4.50/-1.25x160	0
11	F	27	-5.00/-0.50x050	0
12	M	38	-7.50/-0.75x075	0.1
13	F	38	-2.75/-2.00x100	0.02
14	M	22	-1.50/-0.25x140	0
15	F	32	-6.25/-0.75x165	0
16	F	25	-8.00	0
17	F	25	-3.75/-0.50x180	0.08
18	F	41	-7.00/-2.25x175	0.02
19	F	38	-6.75/-0.50x180	0.02
20	F	39	-5.75/-0.75x170	0
21	F	30	-9.00/-0.50x165	0
22	M	38	-6.75/-1.00x180	0.02
23	F	34	-1.00/-4.00x180	0.02
24	F	30	-2.25/-0.25x090	0

Table A7.6. Spreadsheet for Experiment 6 showing postoperative refractive error and postoperative visual acuity of the subjects.

	1 day after			1 week after			1 month after		
Subject	Refractive error	Unaided VA	Aided VA	Refractive error	Unaided VA	Aided VA	Refractive error	Unaided VA	Aided VA
01	0.00/-0.50x025	0.04	0.00	0.00/-0.25x025	0.04	0.00	0.00/-0.25x020	0.00	-0.02
02	+0.50/-0.50x045	0.04	0.00	+0.25/-0.50x045	0.04	0.00	+0.50/-0.50x030	0.02	0.00
03	-0.25/-0.50x145	0.06	0.00	-0.25/-0.25x145	0.06	0.00	-0.25/-0.25x145	0.02	-0.08
04	+1.25/-0.75x160	0.10	0.02	0.75/-1.25x160	0.10	0.02	+0.50/-1.00x170	0.06	0.00
05	-0.25/-0.50x160	0.04	0.00	-0.25/-0.50x160	0.04	0.00	-0.25/-0.50x160	0.02	0.00
06	+0.25/-0.50x150	0.02	0.00	+0.25/-0.50x140	0.02	0.00	+0.25/-0.25x140	0.00	-0.02
07	+0.50	0.02	-0.1	+0.75	0.02	-0.10	+0.25	0.00	-0.1
08	+0.25/-1.00x140	0.04	0.02	+0.25/-1.00x150	0.02	0.00	0.00/-0.75x140	0.00	0.00
09	0.00/-0.75x140	0.26	0.22	0.00/-0.75x120	0.20	0.00	-0.50/-0.75x120	0.16	0.00
10	+0.50/-0.50x180	0.10	0.08	+0.25/-0.50x170	0.06	0.00	-0.25/-0.50x175	0.06	0.00
11	+0.25/-0.25x095	0.04	0.00	+0.25	0.00	-0.10	+0.25/-0.25x080	0.00	-0.02
12	+0.50/-1.00x165	0.6	0.52	+0.50/-1.00x165	0.40	0.36	+0.75/-1.00x160	0.40	0.30
13	+0.25	0.00	-0.10	0.00/-0.50x090	0.02	0.00	0.00/-0.50x090	0.02	0.02
14	0.00/-0.25x090	0.04	0.00	-0.25/-0.25x090	0.06	-0.10	0.00/-0.25x090	0.02	0.00
15	0.00/-0.75x045	0.10	0.08	0.00/-0.75x045	0.06	0.00	-0.25/-0.50x040	0.02	-0.10
16	+0.50/-1.25x180	0.22	0.12	0.00/-1.00x175	0.24	0.18	0.00/-1.00x170	0.10	0.02
17	-0.50	0.04	0.00	-0.25/-0.25x180	0.08	0.00	-0.25/-0.50x180	0.02	0.00
18	+0.25/-1.00x145	0.12	0.08	-0.75/-0.50x135	0.24	0.12	-1.00/-1.00x135	0.36	0.20
19	+0.75/-1.00x145	0.18	0.10	+1.00/-1.00x145	0.30	0.22	+1.00/-1.00x140	0.08	0.02
20	-0.25/-0.50x165	0.10	0.00	+0.25/-0.50x165	0.08	0.00	0.00/-0.50x165	0.08	0.00
21	+0.75	0.08	0.08	+0.50/-0.75x085	0.06	0.08	-0.50	0.26	0.20
22	0.00	0.00	0.00	0.00/-0.75x180	0.12	0.00	-0.25/-0.75x170	0.10	0.00
23	0.00/-0.50x145	0.00	-0.08	0.00/-0.50x145	0.00	-0.02	0.00/-0.75x155	0.08	0.02
24	-0.50	0.00	-0.02	0.00/-0.25x015	0.02	-0.02	0.00/-0.25x010	0.02	0.00

Table A7.7a. Spreadsheet for Experiment 6 showing the corneal clarity index before and after LASIK of subject.

	Preoperative			1 day after			1 week after			1 month after		
subject	1st	2nd	3rd	1st	2nd	3rd	1st	2nd	3rd	1st	2nd	3rd
01	31.0	28.0	31.0	57.8	58.4	57.4	52.7	54.1	46.9	33.0	32.0	31.5
02	30.0	26.0	30.0	33.6	37.3	34.0	30.0	32.0	34.0	31.0	31.5	33.6
03	72.0	74.0	83.0	143.0	144.4	148.1	106.0	100.5	98.8	97.6	88.0	78.0
04	39.0	40.0	41.0	90.0	81.0	92.0	--	84.0	79.0	47.8	40.1	45.4
05	153.0	152.0	153.2	147.3	154.9	156.0	165.8	164.3	158.3	155.1	146.9	150.9
06	107.7	114.5	115.0	124.2	140.2	154.3	119.6	123.8	122.6	118.3	124.6	117.6
07	134.8	110.1	105.8	143.9	153.4	129.0	119.8	113.9	119.1	116.1	106.6	107.2
08	99.6	100.3	95.3	117.7	121.6	135.6	99.1	100.2	97.8	97.8	100.8	100.9
09	141.2	133.6	131.6	151.3	152.0	151.5	140.9	143.4	137.2	138.3	136.0	137.2
10	136.8	143.1	139.4	147.5	140.5	145.9	132.1	135.2	140.6	134.4	133.3	129.4
11	126.5	128.2	111.4	134.0	139.4	139.5	--	127.5	125.5	128.5	127.4	131.9
12	126.1	127.8	128.0	153.2	155.4	158.1	124.7	121.2	121.5	123.3	118.4	131.3
13	169.4	167.9	178.2	175.7	176.3	187.3	171.3	176.0	166.8	171.0	169.4	169.5
14	155.4	149.1	153.7	186.0	181.9	184.3	156.8	161.7	162.1	151.5	152.4	150.6
15	155.3	152.2	148.6	177.8	173.6	171.3	167.9	167.2	169.5	152.5	153.8	154.8
16	154.7	150.4	159.2	166.2	172.2	178.9	165.7	170.4	170.5	153.2	152.1	154.8
17	149.2	140.8	140.5	170.1	170.4	170.5	168.0	167.0	167.8	151.0	156.5	152.4
18	170.0	162.1	161.0	183.1	183.1	191.1	175.0	175.0	175.6	162.1	164.4	162.3
19	161.8	167.7	169.3	195.9	204.7	186.4	173.6	179.8	181.6	165.5	164.1	166.3
20	148.2	141.7	144.4	172.5	170.8	172.1	157.1	158.7	155.7	141.1	143.5	142.3
21	164.2	166.0	158.9	172.0	171.1	171.4	169.1	168.8	170.9	162.2	161.4	164.5
22	158.0	160.6	159.8	179.8	175.2	183.3	166.7	160.7	168.7	158.4	156.2	157.4
23	175.8	169.1	169.8	181.8	178.6	186.2	170.6	171.7	169.1	168.8	167.4	170.0
24	167.5	168.9	161.6	181.2	186.5	184.6	52.7	54.1	46.9	166.4	165.0	167.8

Table A7.7b. Spreadsheet for Experiment 6 showing the central corneal clarity index before and after LASIK of subject.

	Preoperative			1 day after			1 week after			1 month after		
subject	1st	2nd	3rd	1st	2nd	3rd	1st	2nd	3rd	1st	2nd	3rd
01	71.63	51.67	69.50	101.2	98.5	105.4	88.72	81.79	71.17	70.25	68.4	64.58
02	59.82	55.84	65.50	85.4	87.32	90.1	71.2	69.4	73.6	61.35	63.4	60.25
03	99.58	103.86	98.43	189.18	192.11	206.82	163.11	141.09	154.99	126.67	130.5	128.54
04	66.35	76.11	72.45	125.32	114.77	126.85		105.4	111.88	86.45	80.79	77.98
05	178.91	180.40	183.23	207.87	210.71	204.33	210.49	213.02	210.21	190.52	178.3	180.29
06	166.73	177.58	175.50	203.40	210.66	218.54	191.51	182.9	185.55	163.51	176.56	169.44
07	170.67	149.45	156.94	185.89	177.71	180.84	180.91	165.51	156.41	158.47	158.24	159.87
08	150.12	151.09	146.19	163.38	179.47	184.21	144.17	151.25	148.91	138.02	149.57	137.08
09	186.80	181.72	180.01	207.31	193.55	200.16	195.34	188.96	200.53	191.11	188.45	194.21
10	200.61	207.89	202.38	218.07	223.55	222.55	222.78	214.97	222.57	207.98	205.4	210.11
11	212.92	210.76	210.82	223.07	235.84	232.08		217.9	208.94	205.45	210.23	211.8
12	203.77	201.25	208.66	221.50	225.65	223.33	202.3	205.34	201.9	200.1	205.87	203.56
13	212.88	219.78	221.37	234.23	237.12	229.8	222.5	224.78	228.65	219.9	221.56	223.4
14	237.39	234.56	232.78	249.34	244.77	241.96	240.12	242.4	238.56	236.75	234.1	240.64
15	223.40	230.75	226.87	246.15	245.14	244.08	244.12	246.93	240.43	231.3	230.2	227.56
16	213.41	212.76	218.54	245.45	248.41	244.1	233.65	239.57	234.12	221.4	219.7	223.56
17	227.62	230.96	224.78	244.98	250.23	248.56	233.56	234.7	231.65	235.2	234.6	234.1
18	225.12	220.89	219.97	248.12	245.87	249	237.34	236.9	238.79	231.34	234.56	229.87
19	200.56	209.34	205.56	247.84	251.2	253.1	240	241.34	243.56	221.12	216.89	209.14
20	201.45	198.78	195.78	234.56	241.78	246.33	219.98	222.45	221.56	205.45	209.78	203.45
21	221.45	228.70	223.45	233.33	236.65	231.45	230.87	229.89	236.34	227.54	220.56	224.56
22	214.94	218.89	211.76	240.45	238.78	241.67	233.1	231.18	235.91	216.34	212.69	219.71
23	225.34	219.81	227.54	241.89	244.76	239.67	231.23	226.56	223.01	221.2	223.4	219.67
24	211.31	214.78	209.54	247.45	248.91	250.1	233.5	236.78	230.67	225.23	221.78	208.67